# RECHARGE AREAS AND GEOLOGIC CONTROLS FOR THE COURTHOUSE-SEVENMILE SPRING SYSTEM, WESTERN ARCHES NATIONAL PARK, GRAND COUNTY, UTAH

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**FINAL CONTRACT REPORT** January 13, 2003

*View southeast of Courthouse Wash downstream from its confluence with Sevenmile Canyon*

DISCLAIMER

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## ABSTRACT

The Courthouse-Sevenmile spring system, located in Courthouse Wash and Sevenmile Canyon along the western boundary of Arches National Park, supports the base flow of Courthouse Wash and a riparian ecologic system. In this study we characterize the hydrogeology of this spring system and delineate the recharge areas contributing to its flow. The purpose of the study is to assist the National Park Service and Utah Division of Water Rights in establishing limits on future ground-water withdrawals in the area that will maintain the present flow of the Courthouse-Sevenmile spring system and the quality of the Courthouse Wash ecologic system. The study includes geologic analysis, geochemical and physical characterization of spring water, and calculations of the recharge areas for the springs. Geochemical and flow data were collected from Courthouse Wash Boundary Spring and Sevenmile Canyon Boundary Spring, but the data represent physical conditions throughout the Courthouse-Sevenmile spring system.

Courthouse Wash and Sevenmile Canyon partition the Courthouse-Sevenmile spring system into three geographic groups with distinct recharge areas. The northern group includes Courthouse Wash Boundary Spring and two springs along the west wall of Courthouse Wash north of the confluence with Sevenmile Canyon, and derives its flow from bedrock to the northeast, north, and northwest. The eastern spring group is along

the east wall of Courthouse Wash and derives its flow from bedrock east of Courthouse Wash. The western spring group, including Sevenmile Canyon Boundary Spring, is along the south wall of Sevenmile Canyon and the west wall of Courthouse Wash below the confluence with Sevenmile Canyon, and derives its flow from bedrock southwest of the confluence.

The shallow Moab Member aquifer is the dominant source of flow in the Courthouse-Sevenmile spring system, based on the following observations:

1. All springs and seeps in the Courthouse-Sevenmile spring system issue from the Moab Member aquifer, which consists of well-sorted, calcite-cemented, densely jointed eolian sandstone of the Moab Member of the Jurassic Curtis Formation. Most discharge is from the basal contact or from cross-bed-truncation surfaces within 25 feet (8 m) of the base of the Moab Member, except for Courthouse Wash Boundary Spring and one spring in the northern group, which issue from cross-bed planes near the top of the Moab Member.
2. The chemistry, temperature, pH, and dissolved oxygen content of spring water from the eastern and western spring groups indicate that water discharging from the Courthouse-Sevenmile spring system is part of a shallow aquifer system with a relatively short (about 50 years) travel time between recharge and discharge areas, and that water chemistry is affected mainly by dissolution of calcite cement in the Moab Member. Spring-water chemistry also suggests that recharge to most of the Moab Member shallow aquifer occurs solely by infiltration of precipitation

on Moab Member outcrops. Courthouse Wash Boundary Spring water, in contrast, has a slightly saline geochemical signature, suggesting mixing of water of the Moab Member aquifer with water that has passed through other geologic units. The most likely sources for the saline water are (1) alluvium in Courthouse Wash, derived in part from the Jurassic Morrison Formation and the Cretaceous Mancos Shale, both exposed upstream from the spring, and (2) water that has percolated through the Morrison and/or Summerville Formations into the Moab Member aquifer where it underlies these formations west and north of Courthouse Wash Boundary Spring.

3. Geologic boundary conditions partly control ground-water flow to the springs. Ground-water flow follows the regional dip directions of the limbs of the Courthouse syncline, whose axis approximately coincides with Courthouse Wash. The Moab fault severs the Moab Member aquifer on the southwest, and forms an impermeable barrier to horizontal ground-water flow from the southwest into the study area. The eroded southwestern limb of the Salt Valley anticline forms the northeastern boundary of the Moab Member aquifer. The Jurassic Summerville and Morrison Formations form a low-permeability layer above the Moab Member, impeding major recharge to the Moab Member aquifer by infiltration of precipitation where they overlie it.

We used water-budget and catchment-area methods to estimate the land-surface area needed for recharge of the Moab Member aquifer contributing to discharge from

Courthouse Wash Boundary Spring, Sevenmile Canyon Boundary Spring, Poison Ivy Spring, and Sleepy Hollow Spring, and a volumetric travel-time method to estimate the aquifer area contributing to these springs. The water-budget method yields recharge-area estimates of about 1.05 square miles (2.4 $km^2$) for Courthouse Wash Boundary Spring, 0.67 square miles (1.5 $km^2$) for Sevenmile Canyon Boundary Spring, 0.35 square miles (0.8 $km^2$) for Poison Ivy Spring, and 0.64 square miles (1.5 $km^2$) for Sleepy Hollow Spring. The catchment-area method yielded similar results. Recharge areas estimated using the travel-time method are about 25 percent of the areas estimated from the water-budget and catchment-area methods.

Based on the ratios of recharge area to flow for the springs and measured and estimated flows from springs and seeps in the rest of the eastern and western spring groups, the eastern spring group requires about 2.04 square miles (5.3 $km^2$) of recharge area to support its flow and the western spring group requires about 1.5 square miles (3.9 $km^2$) of recharge area to support its flow.

Courthouse Wash Boundary Spring and the rest of the northern spring group are directly connected to the confined Moab Member aquifer which underlies private and state-owned land west of the Arches National Park boundary. Ground-water levels and the base of the Moab Member aquifer below this land both slope toward Courthouse Wash, suggesting a component of ground-water flow in that direction. Recharge from the confined Moab Member aquifer in this area, therefore, contributes an unspecified amount of flow to Courthouse Wash Boundary Spring. Future increases in ground-water

withdrawal from the Moab Member aquifer below these lands could strongly impact the flow of Courthouse Wash Boundary Spring.

The western spring group receives recharge from the unconfined part of the Moab Member aquifer southwest of Courthouse Wash and Sevenmile Canyon. Our calculations indicate that the land-surface area required to support the observed flow of the western spring group is comparable to the outcrop area of the Moab Member upgradient of the springs. The western spring group is, therefore, highly vulnerable to contamination and withdrawal of ground water from the Moab Member aquifer southwest of Courthouse Wash and Sevenmile Canyon. Existing water wells nearby are screened in the Cutler Formation in the footwall of the Moab fault, whereas the source area for the western spring group is in the hanging wall of the fault. Because the Moab fault is considered a ground-water barrier, these wells do not likely affect ground-water flow to the western spring group.

## INTRODUCTION

Courthouse Wash, the only perennial stream in the southwestern part of Arches National Park, supports a stable riparian environment that is critical to the ecology of the Park and adjacent areas (figure 1). Springs and seeps along the canyon walls of Courthouse Wash and lower Sevenmile Canyon in and adjacent to the western part of

Arches National Park provide the base flow for Courthouse Wash (figures 2 and 3). Due to relatively small flows and its location in a desert environment, the Courthouse Wash hydrologic/ecologic system is considered highly vulnerable to long-term changes in volume and quality of recharge. Current and future ground-water development on private and state-owned land adjacent to the western Park boundary (figure 3) may, therefore, affect the quantity and quality of water issuing from the springs and seeps feeding Courthouse Wash, and relatively small long-term changes in spring flow could strongly impact this ecologic system.

This study, performed at the request of and in cooperation with the National Park Service, characterizes the geologic controls and delineates the recharge areas for the springs and seeps that feed Courthouse Wash in and adjacent to western Arches National Park. Our work focuses on two of the major springs feeding Courthouse Wash, informally referred to by the National Park Service as Courthouse Wash Boundary Spring and Sevenmile Canyon Boundary Spring (figures 2 and 3; plate 1). Data from this report will be used by the National Park Service and the Utah Division of Water Rights to establish limits on future ground-water appropriations in the study area, to preserve the present environmental quality and ecologic stability of Courthouse Wash.

The National Park Service chose to focus on Courthouse Wash and Sevenmile Canyon Boundary Springs for this study because they appeared representative of the larger Courthouse-Sevenmile spring system and vulnerable to additional future ground-

water withdrawal by wells in the study area, and due to the feasibility of measuring their discharge compared to other springs in the system. Data from individual springs presented in this report represent conditions in the Courthouse-Sevenmile spring system.

The Sevenmile Canyon and Courthouse Wash surface drainage consists of about 162 square miles (420 $km^2$) in the Kane Springs accounting unit of the Upper Colorado-Dolores subregion of the Upper Colorado River Basin (Seaber and others, 1987). The surface drainage encompasses the Courthouse-Sevenmile spring system, a small commercial development, and undeveloped rural land. The study area for this report encompasses the Courthouse Wash and Sevenmile Canyon surface drainage areas west of Arches National Park and the area within the portion of the western Park containing the major springs and seeps of the Courthouse-Sevenmile spring system (figure 3). The "Courthouse Wash-lower Sevenmile Canyon area" lies within the broadly defined study area and includes about 30 square miles surrounding the Courthouse-Sevenmile spring system (plate 1).

Our approach to delineating the recharge area for the Courthouse-Sevenmile spring system included (1) determining the geologic controls on ground-water flow and spring location, (2) developing a conceptual model for the ground-water flow system contributing to spring discharge, and (3) estimating recharge areas for groups of springs and seeps with common recharge areas. Geologic work included field examination of springs and seeps and major structures to determine the influence of stratigraphy and structure on spring location, and quantitative and qualitative description of joints and faults that may influence ground-water flow. We developed a conceptual model for ground-water flow and spring discharge by considering a wide variety of data, including spring discharge records, field parameters and chemistry of spring water, water levels in

wells, precipitation, hydrostratigraphy, and the hydrogeologic properties of structures. We collected new field-parameter and water-chemistry data for Courthouse Wash Boundary Spring and Sevenmile Canyon Boundary Spring, and also considered previous discharge and chemical data. We estimated land-surface and aquifer areas contributing to spring flow using simple equations, and tailored the shapes and locations of the estimated recharge areas to geologic and topographic boundary conditions and to our conceptual model for ground-water flow.

The principal conclusions of this report are as follows.

(1) Springs in the study area form three geographic groups with distinct recharge areas: the northern group, including Courthouse Wash Boundary Spring, along the west side of Courthouse Wash north of its confluence with lower Sevenmile Canyon; the western group, including Sevenmile Canyon Boundary Spring, along the south side of lower Sevenmile Canyon, and the western side of Courthouse Wash below its confluence with lower Sevenmile Canyon; and the eastern group along the east side of Courthouse Wash (plate 1A).

(2) Geochemical, temperature, and dissolved-oxygen data indicate that the ground-water flow system supplying the Courthouse-Sevenmile spring system is contained entirely in the Moab Member aquifer, except for Courthouse Wash Boundary Spring, which receives some recharge from alluvium in Courthouse Wash and/or the Morrison and Summerville Formations overlying the Moab

Member. The residence time of ground water in the Moab Member aquifer is relatively short, although we lack sufficient data to provide a precise estimate.

(3) Ground water enters the Moab Member aquifer primarily by infiltration of precipitation on outcrops, flows within the Moab Member aquifer down the dip of both limbs of the Courthouse syncline, and discharges in the hinge zone, which is spatially coincident with Courthouse Wash. The area of recharge for the Moab Member aquifer lies entirely within the surface-drainage area for Courthouse Wash and Sevenmile Canyon. North and west of the Courthouse-Sevenmile spring system, the Moab Member aquifer is confined below the Summerville and Morrison Formations. Recharge to the confined Moab Member aquifer may occur by infiltration of precipitation through the Summerville and Morrison Formations, or by southward flow along the Moab fault.

(4) Springs in the study area issue from the contact between the Moab Member of the Curtis Formation and the underlying Slick Rock Member of the Entrada Sandstone, and from cross-bed-truncation planes within the lower 25 feet (8 m) of the Moab Member. Courthouse Wash Boundary Spring and another, unnamed spring in the northern spring group issue from the top of the Moab Member.

(5) We estimated contributing areas for spring flow in the Courthouse-Sevenmile spring system using water-budget, catchment-area, and travel-time methods. The three methods yield reasonable, internally consistent results compatible with our understanding of the hydrogeologic setting and boundary conditions of the Courthouse-Sevenmile spring system.

(6) Courthouse Wash Boundary Spring is directly connected to the confined part of the Moab Member aquifer underlying private and state-owned land to the west and north. The western spring group is connected to the unconfined part of the Moab Member aquifer underlying public lands southwest of Sevenmile Canyon and Courthouse Wash, and the eastern spring group is connected to the unconfined part of the Moab Member aquifer underlying Arches National Park east of Courthouse Wash. All of these springs would be highly vulnerable to future increased ground-water withdrawals or contamination in their recharge areas.

Many geologic terms used in the text are defined in the Glossary at the end of this report.

## GEOLOGIC SETTING

### Regional

The study area is in the Colorado Plateau physiographic province of eastern Utah (Stokes, 1977), characterized by exposures of late Paleozoic and Mesozoic age (see figure A.1 for geologic time scale) sedimentary rocks mantled by thin surficial deposits

and cut by streams and washes that in many places form steep-sided canyons. Bedding throughout the Colorado Plateau dips gently except near relatively widely spaced folds and faults. The Colorado River and its major tributary, the Green River, are the major rivers draining southeastern Utah. Their development has controlled base level, and thus local topography and ground-water flow in the region.

Tectonically, Arches National Park and the study area are in the salt anticline region of the Paradox depositional basin of Pennsylvanian to Permian age (figure 4). The Paradox basin formed as the land surface subsided due to loading of the earth's crust by the hanging wall of the Uncompahgre fault, a northwest-striking reverse fault bounding the northeastern basin margin (figure 4) (Elston and others, 1962; Cater, 1970; Doelling, 1988). The Paradox basin accumulated up to about 10,000 feet (3,050 m) of sediment, including salt, anhydrite, and shale of the Pennsylvanian Paradox Formation; limestone, siltstone, and sandstone of the Pennsylvanian Honaker Trail Formation; and arkosic sandstone and conglomerate of the Permian Cutler Formation (figure 5) (Doelling, 1988, 2001).

Beginning soon after initial deposition of the Paradox Formation and ending in Cretaceous time, buried salt rose as diapirs through overlying sediments (Elston and others, 1962; Cater, 1970; Doelling, 1988). Diapiric movement was most rapid during Permian through Triassic time, and was minimal and localized during Jurassic time. These elongate, northwest-trending diapirs formed the "salt anticlines" of the Paradox basin (figure 4) (Cater, 1970; Doelling, 1988). Intervening synclines formed due to the combined effects of uplift of strata above the salt anticlines and withdrawal of underlying

salt toward the rising diapirs. The linear form and parallel alignment of these diapirs resulted from localization by pre-existing, northwest-striking faults (Cater, 1970; Doelling, 1988). Pennsylvanian through Triassic stratigraphic units thin rapidly and exhibit facies changes toward the salt anticlines, and contain intraformational and interformational angular unconformities due to deposition during ongoing diapirism (Cater, 1970; Doelling, 1988; Hazel, 1994).

Late Cenozoic uplift of the Colorado Plateau led to development of the Colorado River drainage system, accompanied by fluvial erosion that removed thousands of feet of sedimentary rock from the region. Downcutting during Pleistocene time was accompanied by the formation of rock benches and a system of cliff-walled canyons that have been cut into the higher rock benches along major streams and many smaller tributaries. These landforms affect the areal distribution of recharge, discharge, and the movement of ground water (Freethey and Cordy, 1991). During Quaternary time, ground-water circulation caused dissolution and removal of Paradox Formation salt in the cores of several salt anticlines, producing the breached-anticline morphology characteristic of the Salt Anticline section.

Holocene sedimentation is characterized by alternating cycles of alluvial deposition and erosion, with little additional downcutting. Sevenmile Canyon and Courthouse Wash were filled to a depth locally exceeding 50 feet (15 m) with bedded sand, silt, and clay. Sometime within the past 200 years, Sevenmile Canyon and Courthouse Wash were cut down to their present level. Eolian deposits locally cap the canyon rims and benches within the canyons.

## Study Area

Upper Cretaceous through Pennsylvanian bedrock units crop out in the study area (figure 6). Quaternary alluvial and eolian deposits form thin veneers on bedrock, except in washes where they may be up to 50 feet (15 m) thick (Doelling and Morgan, 2000; Doelling, 2001). Exposed in the hanging wall of the Moab fault are: (1) arkosic sandstone of the Permian Cutler Formation, (2) interbedded sandstone and mudstone of the Triassic Chinle and Moenkopi Formations, and (3) sandstone of the Jurassic Wingate Sandstone, the Jurassic Kayenta Formation, and the Navajo Sandstone (figures 6 and 7A; plate 1B). Jurassic rocks crop out in the Courthouse Wash – lower Sevenmile Canyon area (plate 1B), including siltstone, sandstone, and minor limestone and chert of the Morrison and Summerville Formations (figure 7B); eolian sandstone of the Moab Member of the Curtis Formation (figure 7C); eolian and shallow-water sandstone of the Slick Rock Member of the Entrada Sandstone (figures 7C and 7D); and siltstone and fine-grained sandstone of the Dewey Bridge Member of the Carmel Formation (figure 7D) (Doelling and Morgan, 2000; Doelling, 2001). The Moab and Dewey Bridge Members were formerly included in the Entrada Sandstone, but recent stratigraphic work shows that the contacts between these units and the Slick Rock Member correlate with previously established regional unconformities, requiring their assignment to different formations (Doelling, 2001).

The Courthouse syncline and the Moab fault dominate the structure of the study area (figure 6; plate 1B). The broad, open Courthouse syncline formed due to salt withdrawal during formation of the Salt Valley anticline to the northeast (Doelling, 1988). Strata on the limbs of the Courthouse syncline in the study area strike northwest and dip one to five degrees toward the hinge zone (figure 6; plate 1B; cross sections B-B' through E-E', plate 2).

The northwest-striking Moab fault displaces the southwestern limb of the Moab-Spanish Valley salt anticline down to the northeast with a maximum throw of about 2,600 to 3,100 feet (790-945 m) (figures 6 and 8; cross sections B-B' and D-D', plate 3) (Doelling, 1988, 2001; Foxford and others, 1996). Doelling (1988, 2001) interprets the Moab fault as a Tertiary structure, but Foxford and others (1996) present stratigraphic evidence suggesting that it was also active during formation of the salt anticlines in Triassic time.

## HYDROLOGIC SETTING

### Geography and Climate

The study area is in and adjacent to the western part of Arches National Park in south-central Grand County, about 10 miles (16 km) northwest of Moab (figures 3 and 4). The surface elevation in the study area ranges from about 4,300 to 5,890 feet (1,310-1,795 m). The land surface forms a broad plateau capped with small, gently sloped hills and cut by narrow, steep canyons (figure 3; plate 1A). The plateau is developed on the upper surface of the Moab Member of the Curtis Formation, and the capping hills are composed of overlying, less resistant Jurassic and Cretaceous rocks. The steep-sided canyons are cut into and through the Moab Member of the Curtis Formation and into the Slick Rock Member of the Entrada Sandstone (plate 1B).

Altitude and topography influence the movement of air masses and storms, causing temperature and precipitation to vary widely in the region (Freethey and Cordy, 1991). Table 1 presents a summary of average annual temperatures and precipitation at weather stations in and near the study area, and figure 9 shows the areal distribution of precipitation. The weather-station data indicate a dry period from November through June, and a wetter period from July through October. Warm, moisture-laden air masses from the Gulf of Mexico traverse the region in summer, and Pacific air masses and storms dominate the regional weather during October through April (Blanchard, 1990). Because most moisture-bearing air masses come from the south and southeast, the study area is in a rain shadow on the leeward side of the La Sal Mountains (Blanchard, 1990). Based on data from the national Weather Service (2002), average annual precipitation on the mesas and broad outcrop areas ranges from less than 6 inches (15 cm) to a little more than 10 inches (25 cm) and is about 9 inches (23 cm) in the study area (figure 9).

Summer precipitation is sporadic and convectional in nature. Infrequent thunderstorms produce local, high intensity rainfall that cause heavy runoff and may result in flash floods. The storms are distributed randomly in areas of low relief, but are concentrated on and along highlands and result in limited ground-water recharge because they are of short duration, lasting only a few hours. More precipitation falls during the summer than in the winter.

Winter and spring precipitation is chiefly frontal, due to Pacific air masses bringing sustained precipitation to the area. The frontal storms produce either rain or snow, with a small quantity of snow accumulating on the ground for a short while. During fall, winter, and early spring, temperatures are cool, and evapotranspiration is minimal. Precipitation is more evenly distributed, and intensity is generally low allowing for greater ground-water recharge.

Seasonal temperature ranges are wide; temperature extremes at Arches National Park Headquarters are over 100°F (37.8°C) and below 0°F (-18°C) (National Weather Service, 2002). During the summer and fall seasons (July to October) the maximum daily temperature averages about 88°F (56°C), and during the winter season (November to February) the maximum daily temperature is about 49°F (9°C) and can drop below freezing (National Weather Service, 2002). Mean annual temperature is a function of location and altitude, with cooler temperatures found at higher altitudes. Potential evapotranspiration in the study area ranges from 42 to 52 inches (107-132 cm) per year, greatly exceeding annual precipitation (Ashcroft and others, 1992).

## Surface Water

Arches National Park and the study area are drained by the Colorado River, whose deep canyon borders the park on the southeast. Drainages in the area are generally ephemeral and dry, with surface flow caused by extreme but infrequent summer and early fall thundershowers. Perennial reaches of streams are maintained by ground-water discharge and are mostly adjacent to springs. Flows are generally confined to channels, although they frequently inundate the flood plains during extreme thundershowers, where the channels are not deeply incised.

Sevenmile Canyon and Courthouse Wash, which drain into the Colorado River, make up the surface watershed in the study area. The surface drainage area of Sevenmile Canyon to its confluence with Courthouse Wash is about 31 square miles (80 $km^2$). Courthouse Wash above the confluence with the Colorado River, not including Sevenmile Canyon, drains about 131 square miles (339 $km^2$). Sevenmile Canyon has two distinct segments, located approximately east and west of US 191 (figure 3); in this report we informally refer to the segment east of US 191 as lower Sevenmile Canyon. Lower Sevenmile Canyon is steep-sided, narrow, and flat-bottomed along its entire length. Above Sevenmile Canyon Boundary Spring the wash is dry except during extreme precipitation events. Surface flow is present below Sevenmile Canyon Boundary Spring along much of the wash during much of the year, but during the driest part of the year, surface water is limited to isolated pools.

Courthouse Wash can be divided into three geomorphic segments. Upper Courthouse Wash, above Courthouse Wash Boundary Spring, is a dry wash through a broad, gently sloped swale developed on upper Jurassic and Cretaceous sedimentary rocks. Up to about 33 feet (10 m) of alluvial and eolian deposits underlie upper

Courthouse Wash (Doelling and Morgan, 2000). Below Courthouse Wash Boundary Spring, middle Courthouse Wash is a steep-sided, narrow, flat-bottomed canyon cut into and through the Moab Member of the Curtis Formation and the Slick Rock Member of the Entrada Sandstone. Below Arches Highway, lower Courthouse Wash crosses a broad, relatively flat plain then becomes a steep-sided canyon cut into the Navajo Sandstone, the Kayenta Formation, and the Wingate Sandstone.

Data from gauging stations at Arches Highway (1958 to 1966) and near the Colorado River (1951 to 1957 and 1967 to 1986) show that stream flow in Courthouse Wash is highly variable (figure 10) (U.S. Geological Survey, 2002b). We believe that stream flow is controlled by (1) spring discharge, (2) interception of surface runoff, and (3) transmission losses from evaporation, transpiration, and seepage into relatively permeable streambed alluvium below the channel. Stream flow below Courthouse Wash Boundary Spring is locally perennial, and streambed sediments are saturated close to the ground surface. Ground water from the springs and seeps along the canyon walls provides the base flow for the locally perennial reaches of Courthouse Wash. Evaporation from the alluvium and transpiration by phreatophytes reduce the perennial flow. Near the Colorado River the stream flow is more consistent than at Arches Highway, because ground water in the streambed is forced to the surface by bedrock.

The mean annual stream flow at the U.S. Geological Survey gauging station on Courthouse Wash near the Colorado River, from 1941 to 1958 and 1966 to 1989, was about 1.9 cubic feet per second. The average mean stream flow at the U.S. Geological Survey gauging station near the Arches Highway crossing of Courthouse Wash, from 1958 to 1966, was about 1.5 cubic feet per second. We interpret the short duration of measuring at the Arches Highway crossing to indicate problems with that gauging station, and think that the stream-flow data from the U.S. Geological Survey gauging

station on Courthouse Wash near the confluence with the Colorado River is more reliable.

More than 50 percent of the mean monthly stream flow occurs between July and October, when the summer and early fall thundershowers occur. Base flow is stream flow derived from the permanent ground water system, in this case the springs and seeps discharging to Courthouse Wash. Typically, base flow is not subject to wide fluctuations and represents spring and seep discharge minus losses due to evapotranspiration, disregarding storm events. The base flow of Courthouse Wash is about 0.07 cubic feet per second (0.002 $m^3$/sec), determined from flow data from the gauging station near the Colorado River.

## Ground Water

### Recharge

The ground-water recharge rate is an important component of the ground-water flow system, but is difficult to measure or estimate in arid areas where the net water flux is low. The sources of recharge to the Moab Member aquifer are melting snow and rain during the winters and infrequent intense summer thunderstorms and early fall showers. Extreme storm events and flash floods bring large quantities of water for short durations into the recharge area. Water from these events infiltrates through the exposed rock and surficial deposits, but much flows over land to surface drainages. A higher percentage of

snowmelt recharges the aquifer, because the percolation rate is slower and distributed over a longer time period, and occurs when evapotranspiration rates are lower.

Recharge to the Moab Member aquifer is controlled principally by the permeability of the rock; the degree of fracturing; the presence of thin surficial deposits that store precipitation, permitting greater infiltration and decreasing surface runoff; altitude; and physiography. Precipitation infiltrates downward along fractures and through the sandstone matrix. Based on these characteristics in the study area, the recharge potential for the Moab Member aquifer is high; however, the amount of precipitation available for recharge is low.

Estimates of the percentage of annual precipitation that recharges the upper ground-water system are based on the distribution of annual precipitation in the study area and on comparison with previous studies. Rush and others (1982) estimated a long-term annual recharge rate for rocks at depth of approximately three percent of precipitation in the elevation range of 5,000 to 7,000 feet (1,500-2,100 m), based on empirical methods developed by Eakin and others (1951) for desert precipitation recharge. Avery (1986) assumed that five percent of mean annual precipitation becomes recharge to bedrock aquifers in San Juan County, Utah. Price and Arnow (1974) estimated that four percent of the average annual precipitation in the Colorado River basin recharges shallow aquifers. Based on these studies, we estimate that about five percent of the mean annual precipitation falling in the Courthouse-Sevenmile spring area, or about 0.46 inches (1 cm) per year, infiltrates to the Moab Member aquifer.

### Aquifers

Ground water in the study area occurs in two aquifer systems: a regional, deep system that provides ground water to the Colorado River, and a shallow, mostly water-table system, which supplies water to the springs of interest. In the study area, strata above the Dewey Bridge Member of the Carmel Formation comprise the shallow aquifer system, and strata below the Dewey Bridge Member comprise the deep, regional aquifer system. In general, rocks are saturated below the altitude of the Colorado River, and the elevation of the regional potentiometric surface increases with distance from the rivers. Areas of recharge to the ground-water reservoirs of the lower regional aquifers are along the divides of the highlands and ground water moves toward the Colorado River.

The flow path of shallow ground water in the Courthouse Wash-lower Sevenmile Canyon area probably mimics surface-drainage patterns, characterized by flow toward the canyons. Factors controlling the direction, rate, and quantity of water moving through the shallow aquifer system in the study area are: (1) stratigraphy, the nature and extent of the hydrogeologic layers that the ground water moves through; (2) structure, the regional attitude of the hydrogeologic layers, in the area controlled by the Courthouse syncline; (3) the topography of the land surface; and (4) the quantity of precipitation that infiltrates through the rock to recharge the ground-water system.

The Cedar Mountain, Morrison, Curtis, Entrada, Navajo, Wingate, and Cutler Formations yield water to springs and wells in central Grand County (table 2). The quantity and quality of water discharged from these units vary with depth, composition, and hydrogeologic setting. The total-dissolved-solids concentration of water issuing

from springs and water wells in the study area is generally less than 2,000 milligrams per liter, whereas water from petroleum-test wells typically has total-dissolved solids concentrations greater than 20,000 milligrams per liter (Blanchard, 1990, and references therein).

All springs and seeps discharging to Courthouse Wash and lower Sevenmile Canyon in the study area issue from the Moab Member aquifer (figure 11), which is composed of part of the Moab Member of the Curtis Formation. The Slick Rock Member of the Entrada Sandstone underlies the Moab Member and comprises the Slick Rock Member aquifer (figure 5). Blanchard (1990), Freethey and Cordey (1991), and previous workers did not distinguish the Moab and Slick Rock Member aquifers, referring to them together as the Entrada aquifer.

The Moab Member of the Curtis Formation consists of pale tan to white, fine- to medium-grained, well-sorted, cross-bedded sandstone that is moderately to well indurated by calcite cement, and is about 80 to 125 feet (24-38 m) thick (figures 5 and 7C). The sandstone is moderately densely jointed in most places, although joint density increases near the Moab fault. The Moab Member is stratigraphically bounded above by siltstone and fine-grained sandstone of the Summerville Formation and the Tidwell Member of the Morrison Formation (combined as unit Jsmt on figure 6 and plate 1B), and is bounded below by the Slick Rock Member aquifer (figures 5 and 7C). The Summerville and Morrison Formations likely form an aquitard where present, based on their lithology. The contact between the Moab Member of the Curtis Formation and the

Slick Rock Member of the Entrada Sandstone is an unconformity marked by a change from reddish-brown hues of the Slick Rock Member below to pale gray-tan of the Moab Member above (figures 5 and 7C). The unconformity is easily eroded in places, forming a subhorizontal cleft in the canyon wall (figure 2B).

The Moab Member aquifer is a complex sandstone system that has extensive outcrops in low-lying areas and discharges year round in several spring systems. The barren rock surfaces are broken by an intricate system of cliff-walled canyons, and cut by many ephemeral streams. Within the study area, the boundaries of the Moab Member aquifer are erosional to the northeast where it is exposed along the southwest flank of the Salt Valley anticline, and structural to the southwest where it is severed by the Moab fault. Within its outcrop area the Moab Member aquifer is partitioned into three hydrologically isolated compartments by Courthouse Wash and Sevenmile Canyon, which have cut down through the Moab Member into the Slick Rock Member.

The Moab Member aquifer is under both confined and unconfined conditions. At the springs, the upper boundary of the aquifer is a free-water surface, which moves up and down in response to recharge rates. Discharge is thus partially controlled by the recharge rate, with higher recharge resulting in a higher water level, thus higher hydraulic gradients and greater flow to the springs. The Moab Member aquifer is under confined conditions where it underlies the Summerville and Morrison Formations, which are relatively impermeable and obstruct vertical ground-water movement. Thus infiltration of precipitation to the Moab Member aquifer occurs chiefly where the aquifer is exposed.

The Slick Rock Member of the Entrada Sandstone consists of orange- to reddish-brown, fine-grained, well-sorted, planar- to cross-bedded sandstone that is moderately to weakly indurated with calcite cement (figures 5, 7C, and 7D) and is about 180 to 400 feet (55-120 m) thick. Although the Slick Rock Member is an aquifer in some parts of southern Utah (Blanchard, 1990; Freethey and Cordey, 1991), its hydraulic conductivity is apparently lower than that of the Moab Member, presumably due to lower fracture density and/or overall finer average grain size. The Dewey Bridge Member of the Carmel Formation, composed of muddy siltstone to fine-grained sandstone, forms an aquitard below the Slick Rock Member (figures 5 and 7D).

Jobin (1962) estimated hydraulic conductivity of about 1.1 feet per day (0.34 m/day) and transmissivity of about 150 square feet per day (14 $m^2$/day) for the undivided Entrada aquifer, based on laboratory measurements on three core samples from outcrops northwest of Moab. These values are relatively high for a sandstone aquifer (Freeze and Cherry, 1979). Jobin's (1962) tables and maps are insufficiently detailed to locate his sample sites or to distinguish whether these samples were from the Moab Member or Slick Rock Member aquifer.

### Wells and Water Levels

At least 16 water wells are in the study area (table 3; figures 3 and 6; plates 1A and 1B). Seven wells southwest of the Moab fault near US 191 (wells 9 through 15, table 3) are screened in the Permian Cutler Formation. Three wells northeast of the Moab fault are screened in the Moab Member of the Curtis Formation (wells 5 through 7, table 3), one well is screened in the Slick Rock Member of the Entrada Sandstone (well 8, table 3), and two wells are screened in the Morrison Formation (wells 3 and 4, table 3). Useful test data are available only for well 9 (table 3); it is screened in the Cutler Formation, and had a specific capacity of 5.8 gallons per minute per foot of drawdown (72.1 L/min/m) (Utah Division of Water Rights, 2002).

Static water levels are available for 10 of the wells in the study area (table 3). Different workers collected these data at different times, so they cannot be used to construct water-level contours. More than one reading exists for only one well (well 4, table 3), which is monitored by the U.S. Geological Survey (2002a).

Water levels in wells screened in the Moab Member of the Curtis Formation (wells 5, 6, and 7, table 3) are 20 to 90 feet (6-30 m) higher than the elevation of Courthouse Wash Boundary Spring (4,300 feet [1,310 m]), 0 to 78 feet (0-24 m) higher than the elevation of Sevenmile Canyon Boundary Spring (4,320 feet [1,317 m]), and 100 to 178 feet (30-55 m) higher than the elevations of springs in the eastern spring group (4,220 to 4,240 feet [1,286-1,292 m]). These elevation differences indicate an east- to southeast-sloping potentiometric surface in the Courthouse Wash - Sevenmile Canyon

area, and that ground water flows from the area of the wells toward Courthouse Spring. The wells are not likely hydrologically connected to Sevenmile Canyon Boundary Spring or the eastern spring group, due to the intervening canyons.

Water levels are from 100 to 195 feet (30-59 m) lower northeast of the Moab fault than they are southwest of the fault (compare water-level elevations in wells 5, 6, and 7 to those in wells 9 and 13). Because these measurements were made during different months of different years, they are not useful for calculating ground-water gradients, but they suggest that the Moab fault is a hydrologic boundary to horizontal ground-water flow in the shallow aquifer. This inference places important limitations on the possible recharge areas for Courthouse Wash and Sevenmile Canyon Boundary Springs.

Static water levels in wells 5 through 7 (table 3) ranged from about 4,320 to 4,398 feet (1,317-1,341 m) elevation when the wells were drilled. These water levels are about 20 to 98 feet (6-30 m) higher than Courthouse Wash Boundary Spring (elevation 4,300 feet [1,311 m]) and the other springs of the northern group, indicating that some ground water may flow from the confined Moab Member aquifer west of Courthouse Wash to Courthouse Wash Boundary Spring.

**Springs**

Springs in the study area form three geographic groups: the western, eastern, and northern groups (plate 1A). The northern group includes Courthouse Wash Boundary Spring (elevation 4,300 feet [1,311 m]) and two unnamed springs along the west side of Courthouse Wash north of its confluence with lower Sevenmile Canyon. The western group is along the south side of lower Sevenmile Canyon and the west side of Courthouse Wash below the confluence with Sevenmile Canyon, including Sevenmile Canyon Boundary Spring (elevation 4,320 feet [1,317 m]), Poison Ivy Spring (elevation 4,260 feet [1,298 m]), several unnamed springs, and numerous seeps. The eastern group is along the east side of Courthouse Wash, including Sleepy Hollow (elevation 4,220 feet [1,286 m]), Mossy Pool, and Antler Springs, and several unnamed springs and seeps.

Sevenmile Canyon Boundary, Poison Ivy, and Sleepy Hollow Springs are contact springs located in alcoves, issuing from the base of the Moab Member of the Curtis Formation (figures 11A and 11B). The alcoves formed where ground water outflow has concentrated, leading to enhanced weathering and erosion by undermining and collapse at the site of ground water outflow. Courthouse Wash Boundary Spring and the next spring downstream in the northern spring group are diffuse-contact springs emerging near the top of the Moab Member.

Based on their locations along opposite sides of Courthouse Wash and Sevenmile Canyon, the eastern and western spring groups must have different source areas and hydrologic systems. The recharge area for the western group must be southwest of lower

Sevenmile Canyon and Courthouse Wash, and the recharge area for the eastern group must be northeast to east of Courthouse Wash. The recharge area for the northern group is likely the triangular area north of lower Sevenmile Canyon and west of Courthouse Wash, and Courthouse Wash Boundary Spring also likely receives recharge from the confined Moab Member aquifer to the north and northwest. In a later section, we provide more specific estimates for the recharge areas contributing to spring flow.

Blanchard (1990) published flow, specific conductance, and chemical data for samples collected in 1970 by the National Park Service for three springs in the eastern group (table 4). The flow from these springs ranged from 6 to 11 gallons per minute, and total-dissolved-solids concentrations ranged from 143 to 157 milligrams per liter.

The National Park Service measured spring discharge rates at Courthouse Wash Boundary Spring, Sevenmile Canyon Boundary Spring, Sleepy Hollow Spring, and Poison Ivy Spring monthly during 2001 and 2002 (figure 12). The discharge at Courthouse Wash Boundary Spring and Sleepy Hollow Spring was more variable than at Sevenmile Canyon Boundary Spring and Poison Ivy Spring. Peak discharges for all of the measured springs occurred in the winter and minimum discharges occurred in the summer (figure 12). Sleepy Hollow Spring and Courthouse Wash Boundary Spring experienced increased flow in July and August 2001, respectively, in contrast to the other two springs measured.

Courthouse Wash Boundary Spring showed a wider range in flow (from about 17 to 8.5 gallons per minute) than the other three springs measured; its lowest flows occurred in July and September 2001, separated by increased flow in August 2001. This discharge pattern indicates that the annual recharge is significant compared to the water storage capacity of the aquifer supplying flow to Courthouse Wash Boundary Spring.

The flow records for Sevenmile Canyon Boundary Spring and Poison Ivy Spring, both of the western group, are similar, with peak flow in December through March 2001 and minimum flow in July 2001. Sleepy Hollow, of the eastern group, ranged from about 10 to 6 gallons per minute, with peak flow in December through March, and minimum flow in June and September 2001. This discharge pattern indicates that the water storage capacity of the aquifer supplying these springs is large compared to their annual recharge.

The Moab Member aquifer acts as a ground-water reservoir of limited capacity, analogous to a surface-water reservoir. As water is added to the reservoir a greater proportion of the Moab Member aquifer is saturated and ground-water levels within it rise. The fluctuation of ground-water levels affects the discharge of the springs in the Courthouse-Sevenmile spring system differently based on their locations within the aquifer. Courthouse Wash Boundary Spring issues from the top of the Moab Member aquifer, so its discharge is more sensitive to changes in water levels within the aquifer

because it is closer to the top of the saturated zone and the percent change in head at this spring due to water-level fluctuations in the aquifer is relatively high. The other springs measured discharge from the base of the Moab Member aquifer, so their discharges are less sensitive to fluctuations in ground-water levels within the aquifer.

The increased discharge from Courthouse Wash Boundary Spring and Sleepy Hollow Spring during summer may reflect release of water from storage in adjacent alluvium and pools following intense rainstorms that are common during the summer monsoon season. The measuring points for Courthouse Wash Boundary Spring and Sleepy Hollow Spring are both downstream from the main discharge areas, so flow at these points could be affected by factors other than discharge from bedrock. The measuring points for Sevenmile Canyon Boundary and Poison Ivy Springs, in contrast, are much closer to the discharge points, so these measurements do not reflect the postulated release from storage.

The total amount of ground-water discharge in the study area is unknown, although at least 60 gallons per minute (0.14 cubic feet per second) can be estimated based on maximum measured spring discharge. Base flow is at least 0.07 cubic feet per second in the perennial reaches of Courthouse Wash.

# Geochemistry

## Introduction

Total dissolved solids concentrations in ground water in the Colorado Plateau in Utah ranges from less than 100 to more than 390,000 milligrams per liter (Feltis, 1966). Aquifers generally yield fresh water from shallow sources, but the ground water becomes more saline with increasing depth as a result of longer residence time in rocks containing relatively soluble minerals. Within geographically restricted areas, ground water from a single aquifer or group of related aquifers may have a relatively constant chemical character. Water samples from springs issuing from the Moab Member aquifer and similar formations in the Colorado Plateau have total dissolved solids concentrations ranging from 204 to 14,300 milligrams per liter, averaging 5,790 milligrams per liter (Feltis, 1966). Water samples from the Moab Member have low dissolved-solids concentrations, because the sandstone is well sorted and has low soluble-mineral content.

Our geochemical investigations focused on Courthouse Wash and Sevenmile Canyon Boundary Springs, but we also examined available data from other springs in the system. We collected samples for chemical analysis quarterly from June 2001 to May 2002. Sampling was performed several weeks after precipitation events, to avoid contamination by surface water. The chemical character of ground water is principally related to: (1) chemical character of the water as it enters the zone of saturation; (2) distribution, solubility, texture, and adsorption capacity of minerals in the rocks; (3) degree of fracturing, porosity, and permeability of the rocks; and (4) the flow path of the water (Hem, 1985).

## Field Measurements

We measured the temperature, specific conductance, dissolved oxygen, and pH of water from Courthouse Wash and Sevenmile Canyon Boundary Springs in the field for this study (tables 5 and 6). The National Park Service has collected temperature, pH, and specific conductance data at Sleepy Hollow Spring and Willow Spring since 1985 (table 7). The temperature of Courthouse Wash Boundary Spring water was measured at the collection point, where flowing water is most concentrated. Sevenmile Canyon Boundary Spring water was measured near the bedding planes where the water flows out of the rock. Temperatures were read with the thermometer in the water as deeply as possible. Ambient air temperature was measured at the same time as water temperature to check for temperature equilibration. Water temperature varied from 10.24 to 33.1 °C (50-92 °F) for Courthouse Wash Boundary Spring and from 3.1 to 24.56 °C (38-76 °F) for Sevenmile Canyon Boundary Spring (tables 5 and 6 and figure 13). The temperature pattern for both springs is similar to the temperature profile at the Park Headquarters (figure 13), suggesting that the temperature variations observed in the spring waters reflect normal seasonal variations.

Specific conductance varied slightly, ranging from 447 to 644 microsiemens per centimeter for Courthouse Wash Boundary Spring and from 186 to 537 microsiemens per centimeter for Sevenmile Canyon Boundary Spring (tables 5 and 6 and figure 14). Water from the springs is classified as fresh based on specific conductance (Feltis, 1966). The range of pH values was 7.99 to 9.6 for Courthouse Wash Boundary Spring and 7.24 to 8.35 for Sevenmile Canyon Boundary Spring. Typical pH values for ground water range from about 6.0 to 8.5. The pH of these waters shows that they are somewhat alkaline.

Dissolved oxygen ranged from 2.34 to 6.4 milligrams per liter for Courthouse Wash Boundary Spring and from 3.49 to 8.3 milligrams per liter for Sevenmile Canyon Boundary Spring.

### Analytical Data

Analytical results are presented in tables 8 and 9. Courthouse Wash Boundary Spring water has higher total dissolved solids, sodium, chloride, sulfate, total alkalinity, and total hardness and shows greater chemical variability than Sevenmile Canyon Boundary Spring water. Bicarbonate is the dominant anion in all analyses, but chloride is also significant at Courthouse Wash Boundary Spring. Dissolved-solid concentrations are less than 300 milligrams per liter in water from both springs. Neither spring showed significant temporal variation in chemistry.

Trilinear diagrams of major ion concentrations (figures 15 and 16) show that Sevenmile Canyon Boundary Spring discharges water of the calcium-bicarbonate (Ca-$HCO_3$) type having relatively low concentration of total dissolved solids, and Courthouse Wash Boundary Spring discharges water of a sodium-calcium-bicarbonate (Na-Ca-$HCO_3$) type and also has low concentrations of total dissolved solids. Sodium exceeds calcium in water from Courthouse Wash Boundary Spring, but the opposite is true at Sevenmile Canyon Boundary, Sleepy Hollow, Mossy Pool, and Antler Pool Springs (tables 4, 8, and 9).

Calcium to magnesium molar ratios can be used to discern if the water has come into contact with rocks containing dolomite or calcite. Ground water with a Ca/Mg molar

ratio of approximately 1 has been in contact with rocks containing predominantly dolomite, a ratio from 1 to 3 indicates contact with dolomite and calcite, and a ratio greater than 3 indicates contact with calcite (Hem, 1985). The Ca/Mg molar ratio of Courthouse Wash Boundary Spring water ranged from 1.1 to 1.45, whereas Sevenmile Canyon Boundary Spring water ranged from 5.31 to 5.75, and Sleepy Hollow, Mossy Pool, and Antler Pool spring water had values of 8.15, 8.98, and 7.23 respectively. These values represent dissolution of calcite in all of the samples, and contribution from dolomite or some other magnesium-bearing mineral in water issuing from Courthouse Wash Boundary Spring.

Hardness is caused chiefly by calcium and magnesium and in some water by small quantities of strontium and barium. Water of the Courthouse-Sevenmile spring system is moderately hard to very hard. Hardness ranges from 143.5 to 180.6 milligrams per liter $CaCO_3$ (hard to very hard) for Courthouse Wash Boundary Spring, from 119.7 to 210 milligrams per liter $CaCO_3$ (moderately hard to very hard) for Sleepy Hollow Spring, 171 to 359.1 milligrams per liter $CaCO_3$ (hard to very hard) for Willow Spring, and 107.7 to 124.8 milligrams per liter $CaCO_3$ (moderately hard to hard) for Sevenmile Canyon Boundary Spring (tables 4, 8, and 9). Hardness generally increases to the north. The alkalinity of Courthouse Wash Boundary Spring ranged from 162 to 203 milligrams per liter $CaCO_3$ and Sevenmile Canyon Boundary Spring ranged from 99 to 114 milligrams per liter $CaCO_3$.

**Interpretation**

The major-ion chemistry of samples collected during this study indicates two water types. Water from Sevenmile Canyon Boundary Spring is of the calcium-bicarbonate type, and water from Courthouse Wash Boundary Spring is of the sodium-calcium bicarbonate type. The predominance of bicarbonate and calcium and the calcium to magnesium ratios in both types results from dissolution of the calcite cement in the Moab Member aquifer. The distinct chemistry of Courthouse Wash Boundary Spring indicates mixing of water similar to that supplying the other springs in the study area with water that has interacted with another geologic unit. The best candidates for the second source are water from the confined Moab Member aquifer west and north of Courthouse Wash Boundary Spring, and stream alluvium derived in part from the Morrison and Mancos Formations. Water from the confined Moab Member aquifer may acquire its geochemical signature during its path into the aquifer, either by percolation of precipitation from directly above the aquifer or from flow along the Moab fault.

The solubility of oxygen is a function of temperature, pressure, and, to a lesser degree, the salinity of the water (negligible for fresh water). The oxygen in the water reacts with oxidizable materials encountered along its flow path. Based on temperature data, the initial concentration of dissolved oxygen in recharge water for the study area is between 8 and 11 milligrams per liter. Comparison of estimated initial oxygen concentration with values measured at the springs in the study area reveals the fraction of dissolved oxygen retained during flow from recharge area to discharge area. Oxygen consumption in the aquifer depends on the aquifer lithology, especially the occurrence of pyrite and other oxygen-consuming minerals, the availability of organic compounds, and nutrients.

Based on its relatively high dissolved oxygen content, water from Courthouse Wash Boundary and Sevenmile Canyon Boundary Springs probably has limited contact

with, and relatively fast flow through, the Moab Member aquifer. This conclusion is supported by the fact that the spring water shows minor variation in chemistry with time. Variations in spring-water temperature mimic seasonal changes observed at weather stations in the study area, confirming that the springs are part of a shallow flow system. We presently do not have sufficient data to estimate residence time of the spring water within the aquifer.

## GEOLOGIC CONTROLS ON GROUND-WATER AND SPRING FLOW

### Stratigraphic Controls

As noted above, all springs and seeps in the study area except Courthouse Wash Boundary Spring and an unnamed spring in the northern group issue primarily from the unconformity between the Moab Member of the Curtis Formation and the Slick Rock Member of the Entrada Sandstone, and secondarily from cross-bed truncation planes in the lower 25 feet (8 m) of the Moab Member (figures 11A and 11B). The same is true in Courthouse Wash and its side alcoves for about 2 miles (3 km) southeast of the study-

area boundary, and for Willow Spring in Arches National Park about 1.5 miles (2.5 km) northeast of Courthouse Wash Boundary Spring (figures 3 and 6; plates 1A and 1B).

The interformational contact and cross-bed truncation planes accommodate ground-water flow because they localize joints parallel to their surfaces. Gradual dissolution and removal of calcite cement has widened the apertures of these joints, further localizing ground-water flow (Doelling, 1988; Blanchard, 1990). Ground water does not flow downward into the Slick Rock Member because its upper surface is lined with fine-grained, impermeable, white mineral deposits derived from the ground water, preventing flow across the lower joint surface (Blanchard, 1990). The Slick Rock Member may also have lower hydraulic conductivity than the Moab Member due to finer grain size, poorer sorting, and lower joint density.

Water also seeps from joints in Willow Spring wash just above its intersection with Courthouse Wash (figure 17). These seeps form a pool at the mouth of Willow Spring wash, and water from this pool flows through unconsolidated deposits of a small fan at the wash mouth and discharge into Courthouse Wash.

At its point of origin, Courthouse Wash Boundary Spring issues from joints and cross-bed surfaces at the top of the Moab Member of the Curtis Formation (figure 2A). The intersection of Courthouse Wash with the contact between the Summerville

Formation and the Moab Member determines the location of Courthouse Wash Boundary Spring (plate 1B). Ground water in the Moab Member is likely confined upstream (northwest) of this point.

## Structural Controls

### Folds

Understanding the subsurface geometry of the Moab Member-Slick Rock Member contact is crucial to delineating the recharge areas of Courthouse Wash and Sevenmile Canyon Boundary Springs, because this contact strongly influences regional ground-water flow feeding these springs. Using available well and surface data and previously published cross sections (Doelling and Morgan, 2000), we constructed new geologic cross sections (plate 2) and a structure-contour map of the base of the Moab Member of the Curtis Formation (plate 3) to illustrate the subsurface structure in the Courthouse Wash – lower Sevenmile Canyon area. These diagrams show that the Courthouse syncline is an open fold with gently dipping limbs and a broad, poorly defined hinge zone that plunges gently northwest.

The base of the Moab Member forms a gentle, northwest-trending dome-basin structure near Sevenmile Canyon Boundary spring, in the southwest limb of the Courthouse syncline (plate 3). Evidence for this structure includes the elevation of the contact exposed in Sevenmile Canyon, and the log of a nearby petroleum well (well G, table A.1); its shape is otherwise not well constrained. These folds likely formed by small-scale diapirism as discussed above. Some of the irregularity of the contours in this area may be due in part to variations in the stratigraphic thickness of the Moab Member.

The hanging wall of the Moab fault is deformed by a fault-parallel syncline-anticline pair (figure 6; plate 1B; cross sections B-B', D-D', and E-E', plate 2). The anticline probably represents the unbreached northwest continuation of the Moab salt anticline (Doelling, 1988; Foxford and others, 1996). The syncline may have formed from a combination of dissolution-related collapse of underlying units (Doelling, 1988) and displacement on the Moab fault (Foxford and others, 1996).

### Fractures

**Introduction.** Fractures are planar to gently curved mechanical discontinuities in rock, including joints, deformation bands, and faults. It is important to distinguish these fracture types in any hydrogeologic study of fractured bedrock because they influence ground-water flow in different ways.

Joints are simple breaks that form when the rock mass splits into two parts without relative motion on either side of the break. The flow rate of ground water through joints is significantly greater than through the rock matrix, although joints have a much lower capacity for storage. Joints can significantly affect the magnitude and direction of ground-water flow in bedrock aquifers, especially if a predominant, well-connected set exists (Long and Witherspoon, 1985; Ritzi and Andolsek, 1992; Zhang and others, 1996). For example, laboratory measurements on unfractured sample cores of Navajo Sandstone from central Washington County in southwestern Utah yielded an average hydraulic conductivity of 2.1 feet per day (0.6 m/d), whereas well tests yielded hydraulic conductivities of 3.4 to 6.1 feet per day (1-1.9 m/d) (Cordova, 1978). The higher hydraulic conductivity values recorded by the field data are due primarily to joints (Cordova, 1978). A recent aquifer test in the Navajo Sandstone indicated a hydraulic conductivity anisotropy factor of about 24:1 to the northwest, parallel to a set of numerous, long, well-connected joints (Heilweil and others, 2000).

Deformation bands accommodate displacements in porous rock on the order of a few millimeters to a few centimeters, forming thin, resistant, anastomosing bands (Aydin and Johnson, 1978; Antonellini and Aydin, 1994). Deformation bands impede ground-water flow across their planes due to their very fine-grained, poorly sorted internal fabric derived from crushing of the host-rock grains (Antonellini and Aydin, 1994).

Faults may accommodate displacement of tenths of inches to thousands of feet (millimeters to kilometers) between adjacent rock masses, forming a variety of structures in the process. The nature of the material formed in the central part or core of a fault, which accommodates the relative displacement, varies with the composition of the adjacent rocks and the magnitude of displacement (Caine and others, 1996). Typically, fault-core material derived from clay-bearing rocks such as shale or arkosic sandstone is very fine grained, soft, and scaly, whereas fault-core material derived from quartzite or limestone varies from fine-grained gouge to coarse breccia but lacks clay. Retardation of ground-water flow perpendicular to a fault plane increases with increasing clay content, decreasing grain size, and decreasing sorting of the fault-core material (Caine and others, 1996). Dense jointing in the rock mass adjacent to a fault plane, best developed in well-cemented, clay-poor rocks, enhances ground-water flow parallel to the fault plane (Caine and others, 1996).

**Joints.** A digital orthophotograph of the Courthouse Wash-lower Sevenmile Canyon area (figure 18) shows that most joints in the Moab Member of the Curtis Formation strike either northwest or northeast. Field observations made during this study confirmed that most of the lineaments visible on the orthophotograph are joints, that the northwest-striking joint set is the longest and most abundant in most places, and that joints are also developed on cross-bed planes.

To characterize jointing in the Moab Member in the Courthouse Wash - lower Sevenmile Canyon area, we performed reconnaissance field evaluation of joints

throughout the area and quantitative analysis at three sites. The quantitative approach is known as the scanline technique (La Pointe and Hudson, 1985), in which fracture properties are recorded along two perpendicular sampling traverses.

Scanline analyses of joints at three sample sites show that the northwest-striking joint set has the greatest average length, and that northeast-striking joints are typically more closely spaced and more abundant (table 10; figure 19). At sites S1 and S2, the northwest-striking joint set formed first, and one or both ends of the northeast-striking set terminate at northwest-striking joints. This geometry results in good connectivity between the two joint sets. These relations are reversed at scanline site S3 (table 10; figure 19c) and at several other places in the study area.

**Deformation Bands.** Deformation bands are ubiquitous along the Moab fault (see next section), and are common but widely spaced within about one mile of the fault trace. The fault crossing the head of lower Sevenmile Canyon (figure 6; plate 1B) is a tightly spaced cluster of deformation bands, termed a deformation-band zone (Antonellini and Aydin, 1994). Isolated deformation bands are common near this fault, and gradually decrease in abundance to the east. Deformation bands typically form conjugate sets, with the set parallel to the Moab fault most abundant (figure 20).

**Moab Fault.** In the Courthouse Wash-lower Sevenmile Canyon area, the Moab fault strikes northwest, dips 50 to 75 degrees northeast, and juxtaposes the Salt Wash Member of the Morrison Formation in its hanging wall against the lower part of the Cutler

Formation in its footwall (figure 21A; plate 1B; cross sections B-B' and D-D', plate 2). The maximum stratigraphic separation along this section of the Moab fault is about 3,100 feet (945 m) (Doelling, 1988; Doelling and Morgan, 2000, their cross section B-B'). The Moab Member of the Curtis Formation is exposed in the hanging wall of the Moab fault southeast of the study area (figure 8), and the Cedar Mountain and Dakota Formations in the hanging wall are juxtaposed against Jurassic to Cretaceous formations in the footwall in the northwest part of the study area (figure 6).

Fault-related fabrics in the Moab fault core include deformation-band zones, discrete slip surfaces, scaly foliation, silica-cemented fault breccia, and clay-rich gouge (figure 21) (Foxford and others, 1996). Deformation-band zones vary from about 0.5 to 1.5 m thick, and are composed of closely spaced, anastomosing deformation bands (figures 21A, 21B, and 22A). The deformation-band zones are extremely hard due to pervasive silica-cementation (figures 21A and 21B). Most slip surfaces are slickensided, with or without striae (figures 21A, 21B, and 21C), and strike parallel to the Moab fault plane although a variety of orientations are present (figure 22B).

Very hard, silica-cemented fault breccia derived from the Wingate Sandstone is present in the Moab fault core northwest of US 191 (figures 21C and 21D). Clay-rich gouge forms a 1-foot (30.5 cm) thick, light-colored band between hanging wall and footwall rocks in a spectacular road cut along the old Moab Highway, just south of the southern study-area boundary (figure 21E). The scaly-foliated fabric in the Cutler

Formation (figures 21A and 21E) varies from less than one meter to several meters in thickness.

Deformation within about 100 feet (30 m) of the Moab fault plane, in the region known as the damage zone (Caine and others, 1996), is intense and includes deformation bands, discrete slip surfaces, and joints (figures 8, 21E, and 23). These features are best exposed in hanging-wall rocks, and their density decreases steadily away from the main fault plane. Deformation bands in the Moab fault damage zone include a more abundant primary set parallel to the main fault trace and a secondary set forming a conjugate pair with the primary set (figure 21E). Joints in the Moab fault damage zone form two distinct orientation sets striking north-northwest and northeast (figure 22D). The strikes of these joint sets are rotated about 20 degrees clockwise from the strikes of the two main joint sets far from the Moab fault (compare figures 19D and 22D), probably due to local rotation of the regional stress field near the Moab fault.

## Discussion – Effects on Ground-Water Flow

The Moab Member-Slick Rock Member contact and the Courthouse syncline control regional flow patterns in the ground-water system that feeds the Courthouse-Sevenmile spring system. Recharge from precipitation flows downward through joints and through the matrix of the Moab Member to its lower boundary with the Slick Rock Member. Ground water flows along the Moab Member-Slick Rock Member contact toward the syncline axis. Ground water in the northeast limb of the Courthouse syncline flows to the southwest, and flow is to the northeast in the southwest limb. The ground water discharges to Courthouse Wash in the hinge zone of the Courthouse syncline.

The small-scale dome-and-basin structure near Sevenmile Canyon Boundary Spring may locally affect ground-water flow in the Moab Member aquifer by diverting it around the small dome north of Sevenmile Canyon. These folds probably do not significantly affect the ground-water flow system supplying the Courthouse-Sevenmile spring system.

Courthouse Wash closely follows Courthouse syncline, suggesting a genetic relationship. The fold geometry has likely focused surface and ground-water flow to the hinge area, as described above, for thousands to millions of years, causing greater erosion along the hinge and localization of the stream (Doelling, 1988). This probably occurred after erosion removed the Morrison and Summerville Formations, allowing the Moab Member of the Curtis Formation to receive significant recharge from precipitation.

The northwest-striking joint set in the Moab Member of the Curtis Formation likely imparts a northwest-southeast anisotropy of unknown magnitude to ground-water flow, based on orientation, length, and spacing data presented above. In the unconfined part of the Moab Member aquifer, ground water flows primarily along the Moab Member-Slick Rock Member contact and cross-bedding truncation planes within the lower 25 feet (8 m) of the Moab Member. The steeply dipping joints in the unconfined Moab Member aquifer likely provide vertical pathways for infiltration of recharge, but may not strongly influence ground-water flow directions. Flow is distributed through the entire thickness of the confined part of the Moab Member aquifer, and the joints likely exert more control on the ground-water flow direction there.

Deformation-band zones, silicified fault breccia, clayey gouge, and foliated fault rock in the Moab fault core (figure 21) all likely retard ground-water flow perpendicular to the fault plane (Caine and others, 1996). The abrupt change in ground-water levels across the fault, described above, support this inference. High joint density adjacent to the Moab fault (figures 8, 21, and 23) likely enhances fault-parallel flow of ground water (Caine and others, 1996).

# DELINEATION OF RECHARGE AREAS

## Introduction

We delineated the parts of the Moab Member aquifer contributing recharge to the Courthouse-Sevenmile spring system, to better enable Park officials to protect the quality and quantity of water issuing from the springs. Delineation of the recharge areas includes estimating the total area that contributes to spring flow, and delineating the physical boundaries of the recharge areas. Our approach to this problem includes: (1) calculating recharge areas for Courthouse Wash Boundary Spring, Sevenmile Canyon Boundary Spring, Poison Ivy Spring, and Sleepy Hollow Spring; (2) expanding these initial estimates to incorporate flow from other springs in the system; and (3) delineating the recharge areas for Courthouse Wash Boundary Spring and the eastern and western spring groups, based on our conceptual model of recharge, flow, and discharge within the Moab Member aquifer.

## Recharge-Area Calculations

### Introduction

We used water-budget and catchment-area methods to estimate the land-surface areas contributing recharge to individual springs, and a volumetric travel-time method to

estimate an aquifer area needed to supply the springs. These methods involve simple calculations that require little data and are based on assumptions that do not incorporate the hydrogeologic complexities identified in our conceptual understanding of the Courthouse-Sevenmile spring system. The water-budget and catchment-area methods do not predict the shape or location of the contributing area; this must be estimated based on the hydrogeologic setting of the springs.

The water budget method provides a good estimate of the size of the area contributing recharge to springs and seeps that obtain water from local precipitation and no other sources. The catchment area method uses a graph presented in Todd (1980, fig. 2.16, p. 49), which shows the relationship between recharge area, annual recharge, and spring discharge. The volumetric travel-time method defines an aquifer area contributing to the spring, but not a land-surface recharge area in contrast to the other two methods. The aquifer area estimated from the travel-time method should be smaller than the land-surface recharge areas estimated from the water-budget and catchment-area methods.

### Methods and Results

Table 11 summarizes flow data and related statistics for Courthouse Wash Boundary Spring, Sevenmile Canyon Boundary Spring, Sleepy Hollow Spring, and Poison Ivy Spring. Precipitation in the study area from 1987 through 2001 was 60 to 85 percent of normal. Because the Courthouse-Sevenmile spring system is a relatively shallow, low-volume system, we assume that its discharge is strongly affected by this period of decreased precipitation. Discharge measurements used to estimate spring recharge areas should be conservative in order to account for factors not included in the

assumptions of the equations, and to provide maximum protection of discharge and water quality. For these reasons, we used the maximum discharges measured for each spring in our recharge-area calculations (see table 11). The maximum flow value for Poison Ivy Spring was increased by 30 percent for use in the equations to account for the fact that a substantial amount of its discharge was not captured at the measuring point.

**Water-budget method.** The area contributing recharge to a shallow water-table aquifer, in most hydrogeologic settings, is related to spring discharge and local recharge rate. Assuming a steady-state water budget, this can be computed as (Bishop, 2001)

Eq. 1
$$A = \frac{Q}{R}$$

Where: A is land-surface recharge area in square feet,

Q is spring discharge in cubic feet per year, and

R is ground-water recharge rate in feet per year.

Ground-water recharge in the study area is about 0.46 inches per year (0.04 ft/yr) (1 cm/year). Courthouse Wash Boundary Spring requires a recharge area of about 1.05 square miles (2.7 $km^2$) to support a discharge of 16.72 gallons per minute (0.06 $m^3$/min). Sevenmile Canyon Boundary Spring requires a recharge area of 0.67 square miles (1.7 $km^2$) to support a discharge of 10.57 gallons per minute (0.04 $m^3$/min). Sleepy Hollow Spring requires a recharge area of 0.64 square miles (1.7 $km^2$) to support a discharge of 10.02 gallons per minute (0.04 $m^3$/min). Poison Ivy Spring requires a recharge area of

0.35 square miles (0.9 $km^2$) to support a discharge of 5.63 gallons per minute (0.02 $m^3$/min).

The water-budget equation is equally sensitive to uncertainties in spring discharge and aquifer recharge. We estimated the probable ranges of these parameters for Courthouse Wash Boundary Spring, based on values obtained or estimated during the study, to provide an example of the sensitivity of the recharge-area estimates (table 12). Within the estimated ranges of hydrologic parameters for Courthouse Wash Boundary Spring, the recharge area can vary up to four times in size (comparing results using maximum spring discharge and minimum recharge rate to results using minimum spring discharge and maximum recharge rate). The recharge area calculation is slightly more sensitive to the range in recharge rate than the range in spring discharge (table 13).

**Catchment-area method.** We calculated hypothetical catchment areas for the springs, based on recharge and discharge estimates, using the graphical method of Todd (1980, p. 49). These recharge-area estimates are highly sensitive to the value of recharge, which is not confidently known for the study area. Thus, the results are subject to significant uncertainty. Courthouse Wash Boundary Spring requires a catchment area of 1.2 square miles (3 $km^2$) to supply 16.72 gallons per minute (0.06 $m^3$/min) to the spring. Sevenmile Canyon Boundary Spring requires a catchment area of 0.73 square miles (1.9 $km^2$) to supply 10.57 gallons per minute (0.04 $m^3$/min) to the spring. Sleepy Hollow Spring requires a catchment area of 0.66 square miles (1.7 $km^2$) to supply 10.02 gallons per minute (0.04 $m^3$/min) to the spring. Poison Ivy Spring requires a catchment area of 0.34 square miles (0.9 $km^2$) to supply 5.63 gallons per minute (0.02 $m^3$/min) to the spring.

**Travel-time method.** For a spring flowing at a rate Q over a time period $t_i$ the total volume of water discharged is $Qt_i$. The method assumes that a half-cylinder volume of

aquifer focused at the spring supplies the spring flow. This half cylinder has a radius r, thickness b, and effective porosity Θ, and the total volume of water contained therein is ½(Θbπr²). Assuming that there are no long-term storage changes in the aquifer, the water recharging the aquifer must balance the amount of water discharging at the spring. Equating these two volumes of water and solving for area yields (Bishop, 2001)

Eq. 2

$$A = \frac{2Qt_i}{b\Theta}$$

where A is the aquifer area contributing to spring flow, in square feet,

Q is spring discharge in cubic feet per year,

$t_i$ is time of travel in years,

b is average aquifer thickness in feet, and

Θ is effective porosity (dimensionless).

The hydrologic parameters used in this calculation are based on evaluation of data on the Moab Member aquifer. Geochemical evaluation of the springs suggests that the water has only been in the ground for a relatively short time, so we used a travel time of 50 years. Values of effective porosity and average saturated thickness have not been measured in the study area, but were estimated as 0.2 and 80 feet (24 m), respectively, based on data in Freethey and Cordy (1991), Weigel, (1987), and Jobin (1962).

The contributing areas computed using a 50-year travel time area are 0.26 square miles (0.7 $km^2$) for Courthouse Wash Boundary Spring, 0.17 square miles (0.4 $km^2$) for Sevenmile Canyon Boundary Spring, 0.16 square miles (0.4 $km^2$) for Sleepy Hollow Spring, and 0.09 square miles (0.2 $km^2$) for Poison Ivy Spring. These travel-time areas

are about 25 percent of the contributing areas estimated from the water-budget and catchment-area methods for the springs.

The travel-time equation is sensitive to uncertainties in spring discharge; time of travel, which was arbitrarily picked as 50 years; average aquifer thickness; and effective porosity. The recharge area for the springs may vary by about four times in size, and is most sensitive to uncertainties in aquifer thickness as illustrated by the example of Courthouse Wash Boundary Spring (tables 14 and 15).

## Discussion

These recharge-area calculations provide reasonable and consistent estimates of the land surface area and aquifer area supporting flow to the four springs (table 16). We believe that the water-budget method provides the best estimates for the western and eastern spring groups, because it assumes that local precipitation is the sole source of recharge, consistent with the geologic boundary conditions and geochemical data presented above. For Courthouse Wash Boundary Spring, the water-budget and catchment-area methods may be equally applicable because the spring likely receives some recharge from the confined Moab Member aquifer to the west and north. The two methods yield comparable estimates (table 16).

Our estimates of the recharge areas required to support flow in the eastern and western spring groups are less than the outcrop areas of the Moab Member aquifer available to the springs, consistent with geochemical and temperature data indicating that

ground water in this flow system has a relatively short residence time and interacts only with the calcite cement of the Moab Member.

## Delineation of Recharge Areas

As discussed above, Courthouse Wash Boundary Spring, Sevenmile Canyon Boundary Spring, Sleepy Hollow Spring, and Poison Ivy Spring are part of a larger spring system fed by the geographically partitioned, shallow Moab Member aquifer. To estimate the total areas contributing to the western and eastern spring groups, we made rough estimates of the flow from springs and seeps not accounted for in the previous section, and estimated their recharge areas based on the ratios of flow to recharge area for the individual springs as calculated above. We also delineated the recharge area for Courthouse Wash Boundary Spring based on the recharge-area estimates described above. The water budget and catchment area methods provide an estimate of size, but no quantitative information concerning the shape of the land-surface area contributing recharge to the springs. Estimating the shapes and locations of the recharge areas requires inferences based on the local hydrogeologic regime.

We deduced the general direction of ground-water movement from the topography of the watershed. The maximum possible extent of the recharge-area boundaries upgradient of the springs are defined by ground-water flow divides where subsurface flow diverges to supply different spring systems, the physical boundaries of the Moab Member aquifer, and by the canyons that incise and hydrologically partition the aquifer. The areas estimated from the equations above must fit within, and can be

significantly smaller than, these physical limits. The shape of each contributing area is drawn to be consistent with a sloping, anisotropic, non-uniform water table that reflects topography and extends toward inferred topographic and surface-water divides, which are assumed to coincide with ground-water divides.

Courthouse Wash Boundary Spring receives recharge from (1) infiltration of precipitation on Moab Member outcrop northeast of the spring, (2) flow from the confined Moab Member aquifer west and north of the spring, and (3) infiltration of precipitation on alluvium in Courthouse Wash. Although we cannot quantitatively estimate their proportions, we list these sources in their relative order of importance as inferred from our geochemical data. Courthouse Wash Boundary Spring, therefore, has multiple sources of recharge including the confined Moab Member aquifer underlying private and state-owned land to the west and north.

Figure 24 illustrates a schematic recharge area and flow lines for Courthouse Wash Boundary Spring, based on an assumption of radial flow to the spring modified by the dips of both limbs of the Courthouse syncline and constrained by the position of Courthouse Wash and Sevenmile Canyon. Where this recharge area overlies Moab Member outcrop, recharge is by infiltration of precipitation on bedrock and through thin surficial deposits, and the unconfined Moab Member aquifer contributes to the discharge of Courthouse Wash Boundary Spring. Where the recharge area overlies outcrop of Morrison and Summerville Formations, the confined Moab Member aquifer contributes flow to Courthouse Wash Boundary Spring. Figure 24 shows roughly equal contributions from these two sources, but we have not quantified this assumption. We do not have additional hydrogeologic data to better constrain this recharge area.

The eastern spring group is recharged by infiltration of precipitation on Moab Member outcrop east of Courthouse Wash, and includes Sleepy Hollow Spring, for which we estimate a land surface recharge area of 0.64 square miles (1.7 $km^2$) (table 16). Based on qualitative comparison of flow rates, we estimate that the other springs and seeps along the eastern wall of Courthouse Wash collectively require a recharge area of about 0.4 square miles (0.9 $km^2$). The entire eastern spring group, therefore, requires a recharge area of about 1.04 square miles (2.7 $km^2$) to sustain their flows. Figure 24 shows a schematic land-surface area and flow lines contributing to flow in the eastern spring group. Sufficient outcrop area of the Moab Member exists to supply the eastern spring group, and flow is down the dip of the eastern limb of the Courthouse syncline. Courthouse Wash truncates the contributing area on the west.

The western spring group includes Sevenmile Canyon Boundary Spring and Poison Ivy Spring, and is supplied by infiltration of precipitation on Moab Member outcrop south of Sevenmile Canyon and west of Courthouse Wash. The combined estimated recharge area for these two springs is about 1.0 square mile (2.6 $km^2$). A second spring in the same alcove as Poison Ivy Spring has approximately the same discharge, and several other seeps and minor springs discharge from alcoves in the west wall of Courthouse Wash. We estimate that these springs and seeps collectively require a recharge area of about 0.5 square miles (1.3 $km^2$). The western spring group, therefore, requires recharge on about 1.5 square miles (3.9 $km^2$) of land-surface area to sustain their flow. Figure 24 illustrates our best estimate of the land surface area that contributes to the flow of the western spring group. The outcrop area of the Moab Member aquifer south of Sevenmile Canyon and upgradient from the western group of springs is about 2.0 square miles (5 $km^2$), so sufficient outcrop of the Moab Member aquifer exists to supply the observed flow to the western spring group. Sevenmile Canyon truncates the

contributing area on the north and Courthouse Wash truncates the contributing area on the east.

## Conceptual Model of Flow in the Moab Member Aquifer

Based on the data, observations, calculations, and interpretations presented above, we characterize the hydrologic system including the Moab Member aquifer and Courthouse-Sevenmile spring system as follows.

The Moab Member aquifer is unconfined where the Moab Member of the Curtis Formation is exposed, and is likely confined north and west of the Courthouse-Sevenmile spring system where it is buried below about 25 feet (8 m) or more of Summerville and Morrison Formations. Pressure conditions in the Moab Member aquifer are likely gradational between confined and unconfined where it is buried by less than about 25 feet of overburden. Water levels in the wells completed in the confined Moab Member aquifer rise above the top of the aquifer. The entire thickness of the aquifer, therefore, is saturated and the water is under pressure. In contrast, the potentiometric surface is generally below the top of the unconfined Moab Member in its outcrop areas. In these areas only part of the Moab Member is saturated. The potentiometric surface emerges near the top of the Moab Member at the Courthouse Wash Boundary Spring, which is about 6 feet (2 m) below the top of the formation.

Ground-water levels in wells screened in the Moab Member of the Curtis Formation about 2 miles (3.2 km) west of Courthouse Wash Boundary Spring are about 20 to 90 feet (6-27 m) higher than the spring. The structure-contour map (plate 3) indicates that the Moab Member is physically continuous between the two areas. Ground water likely flows from the area of the wells toward Courthouse Wash Boundary Spring and the rest of the northern spring group, and the two areas are likely in direct hydrologic communication.

Recharge to the unconfined Moab Member aquifer occurs by infiltration of precipitation and snowmelt on Moab Member outcrop, and through thin surficial deposits covering outcrops. The geochemistry of spring water and the fine-grained nature of the Morrison and Summerville Formations suggests that infiltration through these units is relatively less important. Ground water collects at the base of the Moab Member and flows along it, due to the high transmissivity of the lower contact of the Moab Member and to the presence of impermeable deposits on the upper surface of the Slick Rock Member.

Courthouse Wash Boundary Spring issues from the top of the Moab Member aquifer and likely receives contributions from both the confined part of the aquifer to the west and north, and from the unconfined part of the aquifer to the east. Comparison of water levels in wells 5 through 8 (table 3) with the elevations of the springs indicates that the potentiometric surface slopes eastward and ground water moves from west to east in

the confined Moab Member aquifer west of Courthouse Wash Boundary Spring. Some ground water likely moves along the Moab fault and recharges the confined part of the Moab Member aquifer. This ground water probably comes from the north and accounts for the higher pressures in the area.

Flow patterns toward the eastern and western spring groups are analogous to the pattern present to the west; ground water flows from the higher areas in the east toward the discharge area in middle Courthouse Wash. The regional dip of the limbs of the Courthouse syncline directs flow toward its axis, which is roughly coincident with Courthouse Wash. The ground water discharges along the base of the Moab Member as springs and seeps in side alcoves of Courthouse Wash and Sevenmile Canyon.

We believe that very little water escapes underground, below the springs and seeps. Accordingly, the springs and seeps are the only large natural outlets of the aquifer, and the aquifer system as a whole is in a steady state condition; that is, the average annual recharge to the aquifer is approximately balanced by the average annual discharge of the springs and seeps. This steady state condition has existed for quite some time as indicated by the riparian ecologic systems that have developed near the springs and seeps.

The potentiometric surface in the Moab Member aquifer fluctuates within limits. In areas where the Moab Member crops out, water infiltrates into the rocks during precipitation events, and the water table rises. The effect of the rise is slowly transmitted by hydraulic pressure down dip to the springs and seeps and a fluctuation, usually small,

of discharge follows. There are no other sources of water to the springs, so increased withdrawal of ground water from the Moab Member aquifer upgradient of the springs and seeps could reduce their discharge. Water levels in the confined Moab Member aquifer area would be even more sensitive to pumping than those in the unconfined aquifer, because the storage coefficient of the confined aquifer is likely considerably less than the specific yield of the unconfined aquifer.

Geochemical data indicate that the residence time of ground water within the Moab Member aquifer is relatively short, consistent with the relatively short and shallow flow path suggested by the geologic setting of the system.

Courthouse Wash Boundary Spring is physically and hydrologically connected with the confined Moab Member aquifer underlying private and state-owned land west and north of the spring, including existing water wells west of the spring. The impact of the existing water wells on spring flow is not known but, based on the well sizes and estimated recharge area (figure 24), is likely minimal. Significant future increases in ground-water withdrawal from the confined Moab Member aquifer would, however, likely decrease the flow of Courthouse Wash Boundary Spring. Ground-water withdrawal from the Moab Member aquifer down the structural dip (generally northwest) from Courthouse Wash Boundary Spring could impact recharge to the spring by reversing the potentiometric-surface gradient. Ground-water withdrawal up dip (generally west and east) from the spring would likely dewater the aquifer locally,

capturing some of the recharge to the spring, before reversing the potentiometric-surface gradient.

The western spring group is supplied by unconfined Moab Member aquifer on public land to the southwest. The Moab Member aquifer is truncated by the Moab fault southwest of the western spring group. Withdrawal of ground water from this relatively small recharge area would strongly impact flow in the western spring group. The recharge area for the eastern spring group is on National Park Service land, so the likelihood of future withdrawal that would impact the flow of these springs is low.

## CONCLUSIONS

Springs in the study area form three geographic groups, separated by canyons cut into, and locally through, the Moab Member aquifer. Each spring group has a distinct and separate recharge area. The northern group, including Courthouse Wash Boundary Spring, is along the west side of Courthouse Wash north of its confluence with lower Sevenmile Canyon; the western group, including Sevenmile Canyon Boundary Spring and Poison Ivy Spring, is along the south side of lower Sevenmile Canyon and the west side of Courthouse Wash below its confluence with lower Sevenmile Canyon; and the eastern group, including Sleepy Hollow Spring, is along the east side of Courthouse

Wash. These springs issue from the shallow Moab Member aquifer in the Jurassic Moab Member of the Curtis Formation. The Moab Member is a fine- to medium-grained, well-sorted, eolian sandstone composed of quartz grains cemented by calcite.

Spring-water chemistry indicates that two types of water are present in the Courthouse-Sevenmile spring system. Courthouse Wash Boundary Spring discharges sodium-calcium-bicarbonate type water, whereas Sevenmile Canyon Boundary Spring and the other sampled springs discharge calcium-bicarbonate type water. Because the springs discharge ground water after relatively short travel times in the subsurface, the water chemistry reflects only near-surface processes (infiltration of meteoric water and reaction with less resistant cements in the rocks). The temporal consistency of water chemistry and discharge from Sevenmile Canyon Boundary Spring and Poison Ivy Spring suggest that only one recharge source and aquifer contribute to the flow of these springs. The slight variability in discharge and the water chemistry of Courthouse Wash Boundary Spring suggest that some of its water comes from outside of the Moab Member aquifer.

Ground-water flow in the Moab Member aquifer is controlled by local topography, the impermeable lower contact of the formation, and regional structure. Ground water flows in the lower part of the Moab Member, above the underlying Slick Rock Member of the Entrada Sandstone. The high hydraulic conductivity of the solution-widened contact, the presence of low-permeability deposits on the top of the Slick Rock Member, and the lower hydraulic conductivity of the Slick Rock Member combine to prevent ground water from percolating below the Moab Member. The limbs of the Courthouse syncline and local topography both slope toward Courthouse Wash and direct ground-water flow to the wash.

Most springs and seeps in the study area issue from the lower contact or from cross-bed-truncation planes within the lower 25 feet (8 m) of the Moab Member aquifer. Courthouse Wash Boundary Spring and a nearby spring in the northern spring group issue from joints and cross-bed planes in the upper part of the Moab Member.

Local precipitation recharges the shallow, unconfined ground-water system in the parts of the Moab Member aquifer that contribute to the flow of the western and eastern spring groups. Recharge results from the downward infiltration of precipitation through fractures and directly into exposed rock of the Moab Member. We estimate that recharge to the Moab Member is about 0.46 inches per year (1 cm/yr). Courthouse Wash Boundary Spring receives recharge from both the unconfined and confined parts of the Moab Member aquifer. The confined Moab Member aquifer is in the subsurface west and north of Courthouse Wash Boundary Spring. Recharge mechanisms to the confined aquifer are uncertain but may include flow from the north in the hanging wall damage zone of the Moab fault, and infiltration of precipitation through the overlying Morrison and Summerville Formations.

We used water-budget, catchment-area, and travel-time methods to estimate the land-surface area contributing to flow in the Courthouse-Sevenmile spring system. Of these methods, the water-budget method provides the best estimate of the size of the recharge area for the western and eastern spring groups because it assumes that they obtain water only from infiltration of local precipitation. Sleepy Hollow Spring of the eastern spring group requires recharge on about 0.64 square miles (1.7 $km^2$) of Moab Member outcrop. The eastern spring group requires recharge on about 1.04 square miles (2.7 $km^2$) of Moab Member outcrop to support its observed flow, consistent with the exposure area of about

7.5 square miles (19 $km^2$) adjacent to and upgradient of the springs. Sevenmile Canyon Boundary Spring requires recharge on about 0.67 square miles (1.7 $km^2$) of Moab Member outcrop to support its observed flow of about 10.57 gallons per minute (0.04 $m^3$/min). The western spring group requires recharge on about 1.5 square miles (3.9 $km^2$) of Moab Member outcrop to support its observed flow, consistent with the existing exposure area of about 2.0 square miles (5.2 $km^2$) adjacent to and upgradient of the western spring group.

The water-budget and catchment-area methods yield similar recharge-area estimates for Courthouse Wash Boundary Spring. Courthouse Wash Boundary Spring requires recharge from about 1.05 square miles (2.7 $km^2$) of the Moab Member aquifer to support its observed average flow of about 16.75 gallons per minute (0.06 $m^3$/min). This recharge comes from the unconfined and confined parts of the Moab Member aquifer in unknown proportions.

Due to their relatively low flows and limited recharge areas, all three spring systems would likely be adversely affected by significant increases in ground-water withdrawal from their recharge areas and adjacent parts of the Moab Member aquifer. Courthouse Wash Boundary Spring is particularly vulnerable, because (1) it marks the farthest upstream point of perennial flow in Courthouse Wash, (2) its flow is most sensitive to changes in water levels and pressure in the Moab Member aquifer, and (3) its recharge area lies below land with the greatest potential for future ground-water development.

## ACKNOWLEDGMENTS

We thank the Water Resources Division of the National Park Service for funding this project. James Harte of the Water Resources Division of the National Park Service facilitated the project. The manuscript was reviewed by James Harte, Paula Cutillo, Larry Martin, and Brad Gillies of the National Park Service, Water Resources Division; Boyd Clayton of the Utah Division of Water Rights; and Ben Everitt of the Utah Division of Water Resources.

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## GLOSSARY

Definitions are from Jackson (1997), with modification by the authors. Many of the terms appear only in the Description of Map Units in appendix A. Italicized words are cross-referenced in the glossary. Some words in the glossary are found only in the definitions of other words, not in the text.

*Alluvial* – Pertaining to or composed of *alluvium.*

*Alluvium* – A general term for clay, silt, sand, gravel, or similar unconsolidated *detrital* material, deposited during comparatively recent geologic time by a stream or other body of running water, as a sorted or semisorted sediment in the bed of the stream or on its flood plain or delta, or as a cone or fan at the base of a mountain slope.

*Anhydrite* – A mineral consisting of anhydrous calcium sulfate: $CaSO_4$.

*Anticline* – A *fold*, the core of which contains stratigraphically older rocks, and is convex upward.

*Aquifer* - A body of rock or sediment that contains sufficient saturated permeable material to conduct ground water and to yield significant quantities of water to wells and springs.

*Aquitard* - An impermeable layer that creates confined ground-water conditions, in which ground water is under pressure significantly greater than that of the atmosphere.

*Arkose* - A *feldspar*-rich sandstone, commonly coarse grained and pink or reddish, that is typically composed of angular to subangular grains that may be either poorly or moderately well sorted; *quartz* is usually the dominant mineral, with *feldspars* constituting at least 25%; matrix commonly includes clay minerals, mica, iron oxide, and fine-grained rock fragments.

*Breccia* – A coarse-grained *clastic* rock composed of angular broken rock fragments held together by mineral cement or in a fine-grained matrix.

*Calcarenite* – A limestone consisting predominantly of sand-size carbonate grains.

*Calcite* – A common rock-forming mineral – $CaCO_3$.

*Chalk* – A soft, pure, earthy, fine-textured, usually white to light gray or buff limestone of marine origin, consisting almost wholly of *calcite*, formed mainly by shallow-water accumulation of calcareous shells of floating microorganisms (chiefly foraminifers) and of comminuted remains of calcareous algae (such as coccoliths and rhabdoliths) set in a structureless matrix of very finely crystalline calcite.

*Chert* – A hard, dense, dull to semivitreous, *microcrystalline* or *cryptocrystalline* sedimentary rock, consisting dominantly of interlocking crystals of quartz less than about 30 microns in diameter, that may also contain impurities such as calcite, iron oxide, and the remains of siliceous and other organisms. It has a tough, splintery to conchoidal fracture, and may be variously colored. Chert occurs as nodular or concretionary segregations (chert nodules) in limestone and dolomite, or as areally extensive layered deposits (bedded chert); it may be an original organic or inorganic precipitate, or a replacement product.

*Clastic* – Pertaining to a rock or sediment composed principally of broken fragments that are derived from preexisting rocks or minerals that have been transported some distance from their places of origin.

*Conglomerate* – A coarse-grained *clastic* sedimentary rock, composed of rounded to subangular fragments larger than 2 mm in diameter typically containing fine-grained particles in the interstices, and commonly cemented by calcium carbonate, iron oxide, silica, or hardened clay; the consolidated equivalent of gravel.

*Conjugate* – Said of two faults formed during the same deformational period and intersecting with an acute dihedral angle.

*Coquina* – A *detrital* limestone composed wholly or chiefly of mechanically sorted fossil debris that experienced abrasion and transport before reaching the depositional site.

*Cross-bed* - A single bed, inclined at an angle to the main planes of stratification.

*Cross-bedding* – Cross-stratification in which the *cross-beds* are more than 1 cm in thickness.

*Cryptocrystalline* – Said of a texture of a rock consisting of crystals that are too small to be recognized and separately distinguished even under the ordinary microscope (although crystallinity may be shown by the use of the electron microscope).

*Detrital* – Pertaining to or formed from *detritus*.

*Detritus* – A collective term for loose rock and mineral material that is worn off or removed by mechanical means, such as sand, silt, and clay, derived from older rocks and moved from its place of origin.

*Diapir* – A dome or anticline in which the overlying rocks have been ruptured by the squeezing-out of plastic core material.

*Dip* - The inclination of a planar surface (for example, bedding or a fault), as measured relative to horizontal and in a vertical plane that is perpendicular to the *strike* of the surface.

*Eolian* – Pertaining to the wind; especially said of such deposits as dune sand and loess, of sedimentary structures such as wind-formed ripple marks, or of erosion and deposition accomplished by the wind.

*Fault* - A discrete surface or zone of discrete surfaces separating two rock masses across which one rock mass has slid past the other.

*Feldspar* – A group of abundant rock-forming minerals, generally divided into two compositional groups, (1) the plagioclase feldspar series: $CaAl_2Si_2O_8$ to $NaAlSi_3O_8$, and (2) the alkali feldspar series: $(K,Na)AlSi_3O_8$.

*Fold* - A curve or bend of a planar structure such as rock strata or bedding planes.

*Foliation* – A general term for a planar arrangement of textural or structural features in any type of rock, especially the locally planar fabric in a rock defined by fissility.

*Footwall* - The lower block of a non-vertical fault.

*Fracture* - A general term for any surface within a material across which there is no cohesion; includes *joint* and *fault*.

*Gouge* - a thin layer of soft, fault-comminuted rock material in the core of a fault.

*Hanging wall* - The upper block of a non-vertical *fault*.

*Hinge line* – The line or boundary between regions of opposite dip in a *fold*.

*Hinge zone* – A broad and/or complex and/or poorly defined *hinge line*.

*Hydraulic conductivity* - A coefficient of proportionality describing the rate at which a fluid can flow through a permeable medium. Hydraulic conductivity is a function of the physical properties of the porous or fractured medium and of the density and viscosity of the fluid.

*Joint* - A planar or nearly planar fracture in rock, along which negligible relative movement has occurred.

*Limestone* – A sedimentary rock consisting chiefly of calcium carbonate, principally in the form of the mineral *calcite*; formed by either organic or inorganic processes, and may be detrital, chemical, *oolitic*, crystalline, or recrystallized; many are highly fossiliferous and represent ancient shell banks or coral reefs; rock types include *micrite*, *calcarenite*, *coquina*, *chalk*, and *travertine*.

*Micrite* - A rock or rock matrix composed of carbonate mud with crystals less than 4 micrometers in diameter.

*Microcrystalline* – Said of a texture of a rock, consisting of crystals that are small enough to be visible only under the microscope.

*Mudstone* - A fine-grained sedimentary rock in which the proportions of clay and silt are approximately equal.

*Normal drag* – A fold that appears to have formed in response to fault motion.

*Normal fault* - A fault along which the *hanging wall* has moved downward relative to the *footwall.*

*Oolite* – A sedimentary rock, usually a *limestone*, made up chiefly of *ooliths* cemented together.

*Oolith* – One of the small round or ovate accretionary bodies in a sedimentary rock. It is usually formed of calcium carbonate, in successive concentric layers, commonly around a nucleus such as a shell fragment, an algal pellet, or a quartz sand grain, in shallow, wave-agitated water.

*Oolitic* – Pertaining to an *oolite*, or to a rock or mineral made up of *ooliths*.

*Permeability* - A coefficient describing the rate at which fluid can flow through a porous or fractured medium.

*Quartz* – Crystalline silica, an important rock-forming mineral: $SiO_2$.

*Reverse fault* - A fault that dips greater than 30 degrees, along which the hanging wall has moved upward relative to the footwall.

*Sandstone* - A medium-grained *clastic* sedimentary rock composed of abundant rounded or angular fragments of sand size and more or less firmly united by a cementing material.

*Shale* - A laminated, indurated rock with >67% clay-sized minerals.

*Siltstone* - An indurated silt having the texture and composition of shale but lacking its fine lamination or fissility.

*Slickenside* - a highly polished surface that is the result of frictional sliding.

*Striae* - plural of striation, defined as one of a series of linear grooves or scratches, generally parallel, inscribed on a rock surface, by faulting as used in the context of this report.

*Strike* - The angle a planar feature makes relative to north, as measured in a horizontal plane.

*Syncline* - A *fold*, the core of which contains stratigraphically younger rocks, and is convex downward.

*Thrust fault* - A *fault* that dips 30 degrees or less, along which the hanging wall has moved upward relative to the footwall.

*Transmissivity* – The rate at which a fluid is transmitted through a unit width of an aquifer under a hydraulic gradient.

*Travertine* – A dense, finely crystalline massive or concretionary *limestone*, of white, tan, or cream color, commonly having a fibrous or concentric structure and splintery fracture, formed by rapid chemical precipitation of calcium carbonate from solution in surface and ground waters as by agitation of stream water or by evaporation around the mouth or in the conduit of a spring, especially a hot spring.

*Unconformity* - A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession.

***Table 1**. Monthly maximum, minimum, and average temperatures and average precipitation at weather stations in and adjacent to the study area (based on data from the National Weather Service [2002]).*

| | Arches National Park HQ | | | | Thompson | | | | Moab | | | | Canyonlands (The Neck) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 4,130 feet elevation (1,259 m) | | | | 5,151 feet elevation (1,570 m) | | | | 3,967 feet elevation (1,209 m) | | | | 5,899 feet elevation (5,899 m) | | | |
| | 1980-2000 | | | | 1948-1994 | | | | 1893-1992 | | | | 1965-2000 | | | |
| | Maximum Temp °F | Minimum Temp °F | Average Temp °F | Average Precip *(inches)* | Maximum Temp °F | Minimum Temp °F | Average Temp °F | Average Precip *(inches)* | Maximum Temp °F | Minimum Temp °F | Average Temp °F | Average Precip *(inches)* | Maximum Temp °F | Minimum Temp °F | Average Temp °F | Average Precip *(inches)* |
| Jan | 42.8 | 20.0 | 31.4 | 0.58 | 37.1 | 14.6 | 25.9 | 0.8 | 42.0 | 18..0 | 30.0 | 0.56 | 36.8 | 20.1 | 28.5 | 0.51 |
| Feb | 50.9 | 26.7 | 38.8 | 0.44 | 45.5 | 22.3 | 33.9 | 0.53 | 51.8 | 25.5 | 38.7 | 0.43 | 44.0 | 25.9 | 35.0 | 0.41 |
| Mar | 62.0 | 35.5 | 48.8 | 0.85 | 55.3 | 29.7 | 42.5 | 0.86 | 51.9 | 34.2 | 48.0 | 0.85 | 53.3 | 32.4 | 42.9 | 0.81 |
| Apr | 70.2 | 41.9 | 56.1 | 0.84 | 66.0 | 37.9 | 52.0 | 0.76 | 71.9 | 41.9 | 56.9 | 0.98 | 62.0 | 38.6 | 50.3 | 0.79 |
| May | 80.9 | 51.1 | 66.0 | 0.76 | 75.6 | 47.0 | 61.3 | 0.88 | 82.3 | 50.1 | 66.2 | 0.72 | 73.1 | 48.5 | 60.8 | 0.79 |
| Jun | 92.3 | 60.4 | 76.4 | 0.43 | 86.9 | 57.1 | 72.0 | 0.43 | 93.1 | 57.5 | 75.3 | 0.48 | 84.2 | 59.0 | 71.6 | 0.48 |
| Jul | 98.1 | 66.9 | 82.5 | .0.90 | 93.1 | 63.9 | 78.5 | 0.69 | 99.1 | 64.1 | 81.6 | 0.83 | 90.3 | 65.1 | 77.7 | 1.02 |
| Aug | 96.1 | 65.9 | 81.0 | 0.99 | 90.4 | 61.5 | 76.0 | 1.0 | 96.5 | 62.8 | 79.7 | 0.88 | 88.1 | 63.2 | 75.7 | 0.83 |
| Sep | 86.6 | 55.5 | 71.1 | 0.80 | 81.6 | 52.6 | 67.1 | 0.94 | 87.3 | 52.8 | 70.0 | 0.75 | 78.6 | 54.6 | 66.6 | 0.87 |
| Oct | 72.6 | 41.6 | 57.1 | 1.33 | 69.5 | 41.1 | 55.3 | 1.07 | 74.4 | 40.8 | 57.6 | 1.16 | 64.8 | 42.8 | 53.8 | 1.22 |
| Nov | 56.2 | 31.0 | 43.6 | 0.69 | 52.1 | 28.2 | 70.2 | 0.64 | 58.3 | 30.6 | 44.5 | 0.74 | 48.6 | 30.8 | 39.7 | 0.74 |
| Dec | 44.0 | 22.3 | 33.2 | 0.45 | 40.4 | 18.1 | 29.3 | 0.59 | 45.1 | 21.4 | 33.2 | 0.65 | 37.9 | 21.5 | 29.7 | 0.61 |
| | Average Temperature °F 57.2 | | | | Average Temperature °F 55.3 | | | | Average Temperature °F 56.8 | | | | Average Temperature °F 50.2 | | | |
| | Total Annual Precipitation 9.06 | | | | Total Annual Precipitation 9.19 | | | | Total Annual Precipitation 9.04 | | | | Total Annual Precipitation 9.08 | | | |

*Table 2. Geologic and hydrologic characteristics of aquifers in the study area. Compiled from Blanchard (1990) and Doelling and Morgan (2000).*

| Geologic Unit[1] | Map Symbol | Thickness in feet (m) | Lithology | General Hydrologic Characteristics | Yield (gallons per minute) | Water Quality[2] | |
|---|---|---|---|---|---|---|---|
| | | | | | | Total Dissolved Solids (mg/L) | Chemistry Type |
| Cedar Mountain | Kcm | 120-200 (37-61) | Interbedded sandstone, conglomerate, and mudstone | Sandstone and conglomerate yield small amounts of water to wells and springs | Springs: < 1<br>Wells: <1 | Spring: 1,020<br>Well: 1,470 | Calcium magnesium sodium sulfate bicarbonate |
| Brushy Basin Member of Morrison Formation | Jmb | 295-450 (90-135) | Mudstone to fine-grained sandstone | Yields small amounts of water to wells and springs | Springs: < 1<br>Wells: < 1 | Spring: 1,020 | Calcium magnesium sodium sulfate bicarbonate |
| Salt Wash Member of Morrison Formation | Jms | 130-300 (40-90) | Interbedded sandstone, conglomerate, and mudstone | Sandstone and conglomerate yield small amounts of water to wells and springs | Springs: < 1<br>Wells: < 1 | Spring: 1,160 | Calcium magnesium sodium sulfate bicarbonate |
| Moab Member of Curtis Formation[3] | Jctm | 70-110 (21-34) | Cross-bedded, well sorted, fine- to medium-grained sandstone, moderately indurated with calcite cement | Yields abundant water to springs and wells | Springs: 0.1-11.1 | Springs: 143-157 | Calcium carbonate; hard to very hard |
| Slick Rock Member of Entrada Sandstone | Jes | 180-400 (55-122) | Cross-bedded, well sorted, fine- to medium-grained sandstone, weakly to moderately indurated with calcite cement | Yields moderately abundant water to springs and wells | No data | Well: 300 | Calcium carbonate; hard to very hard |
| Navajo Sandstone | Jn | 165-800 (50-244) | Cross-bedded, well sorted, fine-grained sandstone, weakly to moderately indurated with calcite cement | Yields abundant water to springs and wells | Springs: <1-5 | Springs: 102-350<br>Well: 210-360 | Calcium bicarbonate to calcium magnesium bicarbonate |
| Wingate Sandstone | Jw | 250-400 (76-122) | Cross-bedded, well sorted, fine-grained sandstone, indurated with calcite cement | Yields moderately abundant water to springs and wells | Springs: 10-240 | Springs: 161-174<br>Well[4]: 280-45,000 | Calcium magnesium bicarbonate; moderately hard to hard |
| Arkosic member of Cutler Formation | Pc | 0-4,000 (0-1,220) | Cross-bedded, medium to coarse-grained sandstone and minor conglomerate. | Yields small amounts of water to wells | Wells: 1-40 | Wells: 1,420-3,450 | Calcium magnesium sulfate; very hard |

Notes

1. See figure 5 and appendix A for additional information. Unit thicknesses are from Doelling and Morgan (2000) and represent ranges from a wider area than shown on the cross sections in this report.
2. Data from petroleum wells not included. Total-dissolved-solids concentrations of water from petroleum wells range from about 2,000 to over 100,000 mg/L (Blanchard, 1990, p. 28).
3. Blanchard (1990) does not differentiate the Moab Member of the Curtis Formation (considered a member of the Entrada Sandstone at the time of his report) from the underlying Slick Rock Member of the Entrada Sandstone. Assignment of Blanchard's (1990) data to the Moab or Slick Rock Member is based on work done as part of this study.
4. Blanchard (1990) reports a measured value of 45,000 mg/L for one shallow well in the Wingate aquifer. He suggests that this anomalous value is caused by an upward gradient moving ground water from the salt-rich Paradox Formation and/or underlying formations into the Wingate aquifer here.

*Table 3*. *Records for water wells in study area*[1].

| ID[2] | Location[3] | Well Diameter (in) | Well Depth (ft) | Screened Interval (ft) | Static Water Level (ft)[4]; Measure Date | Ground Surface Elevation (ft)[5] | Elevation of Static Water Level (ft)[6] | Producing Unit[7] |
|---|---|---|---|---|---|---|---|---|
| 1 | N 350 W 950 SE 23S 20E 31 | 6.0 | 1200 | nd | 85; 5/26/96 | 4570 | 4485 | nd |
| 2 | N 650 E 450 NW 24S 20E 5 | 7.0 | 1160 | 2 to 1078 | 70; 9/1/85 | 4550 | 4480 | Kd-Jctm |
| 3 | S 1012 W 766 E4 24S 20E 16 | 8.6 | 45 | - | - | 4430 | - | Jmb |
| 4 | S 4015 W 750NE 24S 20E 22 | 8.3 | 70 | 46 to 70 | 14.5; 3/3/00 | 4410 | 4395 | Jmb |
| 5 | N 640 W 550 E4 24S 20E 34 | 6.6 | 300 | - | 162; 10/10/78 | 4560 | 4398 | Jctm |
| 6 | N 100 W 480 E4 24S 20E 34 | 6.3 | 400 | 320 to 400 | 220; 6/21/99 | 4560 | 4340 | Jctm |
| 7 | S 2400 E 600 NW 24S 20E 35 | 7.0 | 340 | 280 to 340 | 240; 6/30/93 | 4560 | 4320 | Jctm |
| 8 | 24S 20E 35 | 4.5 | 388 | 328 to 388 | 200; 7/10/94 | 4550 | 4350 | Jes |
| 9 | N 5225 E 858 SW 25S 20E 2 | 6.0 | 200 | 150 to 200 | 15; 2/26/95 | 4530 | 4515 | Pc |
| 10 | N 2700 E 50 SW 25S 20E 2 | 6.0 | 200 | - | - | 4550 | - | Pc |
| 11 | N 2700 E 250 SW 25S 20E 2 | 6.0 | 600 | - | - | 4550 | - | Pc |
| 12 | N 2700 E 530 SW 25S 20E 2 | 8.8 | 100 | - | - | 4550 | - | Pc |
| 13 | N 2700 E 750 SW 25S 20E 2 | 8.8 | 125 | 75 to 105 | 48; 2/16/95 | 4550 | 4502 | Pc |
| 14 | N 1100 W 850 SE 25S 20E 2 | 5.0 | 260 | - | - | 4590 | - | Pc |
| 15 | N 1500 W 20 SE 25S 20E 2 | 6.0 | 550 | 155 to 230 | - | 4540 | - | Pc |
| 16 | N 500 E 700 SW 24S 20E 19 | 7.0 | 665 | - | 200; 1/31/79 | 4780 | 4580 | - |

**Notes**

- no data

1. Data for wells 1-11 from Utah Division of Water Rights (2002) and data for wells 12-16 from U.S. Geological Survey (2002a), except as noted below.
2. Corresponds to well numbers on figures 3 and 6 and plates 1A and 1B.
3. Well locations are in point of diversion notation, explained on figure A.3.
4. Depth below well head. Negative values indicate flowing (artesian) well.
5. Estimated by the authors from 71/2 minute topographic maps with 20-foot contour intervals.
6. Equals ground surface elevation minus static water level.
7. Determined by the authors from cross sections, geologic maps, and well logs. Unit abbreviations correspond to those used in this report-see figure 6 or appendix A.

***Table 4**. Data for three springs along eastern Courthouse Wash, from Blanchard (1990)[1].*

| Spring Name[2] | Location[3] | Altitude (feet) | Date Measured | Discharge (gal/min) | Temperature (°C) | Specific Conductance (µS/cm) | pH (units) | Solids, residue at 180 °C dissolved (mg/L) | Calcium, dissolved (mg/L as Ca) | Magnesium, dissolved (mg/L as Mg) | Sodium, dissolved (mg/L as Na) | Potassium, dissolved (mg/L as K) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sleepy Hollow | (D-24-21)31dab-S1 | 4,220 | 9/1 & 9/15/70 | 8.2 | 13.0 | 225 | 7.7 | 143 | 43 | 3.2 | 2.3 | 1.6 |
| Mossy Pool | (D-25-21)5bbb-S1 | 4,240 | 9/15/70 | 11.0 | 13.0 | 250 | 7.4 | 145 | 49 | 3.3 | 2.6 | 1.1 |
| Antler Pool | (D-25-21)5abb-S1 | 4,240 | 9/15/70 | 6.0 | 12.5 | 270 | 8.0 | 157 | 49 | 4.1 | 3.8 | 1.7 |

| Spring Name | Chloride, dissolved (mg/L as Cl) | Sulfate, dissolved (mg/L as $SO_4$) | Fluoride, dissolved (mg/L as F) | Alkalinity, lab, (mg/L as $CaCO_3$) | Carbon dioxide, dissolved (mg/L as $CO_2$) | Silica, dissolved (mg/L as $SiO_2$) | Hardness, total (mg/L as $CaCO_3$) | Hardness, noncarbonate (mg/L as $CaCO_3$) | Arsenic, dissolved (µg/L as As) | Barium, dissolved (µg/L as Ba) | Iron, dissolved (µg/L as Fe) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sleepy Hollow | 3.5 | 6.5 | 0.4 | - | 4.2 | 10 | 120 | 0 | 0 | - | 0 |
| Mossy Pool | 5.0 | 10 | 0.5 | - | 9.4 | 9.5 | 140 | 0 | 0 | - | 0 |
| Antler Pool | 5.0 | 12 | 0.5 | - | 2.5 | 11 | 140 | 11 | 0 | - | 0 |

| Spring Name | Selenium, dissolved (µg/L as Se) | Strontium, dissolved (µg/L as Sr) |
|---|---|---|
| Sleepy Hollow | 37 | - |
| Mossy Pool | 89 | - |
| Antler Pool | 55 | - |

**Notes**

\- no data

1. Data were collected by the National Park Service and reported in Blanchard (1990). See plate 1a for locations.
2. Blanchard (1990, table 7, p. 36) reports the elevations of all three springs as 4,240 feet.
3. Locations given in U.S. Geological Survey convention – see figure A.4 for explanation.

***Table 5.*** *Field parameters for Courthouse Wash Boundary Spring water.*

| Date of Sample | Water Temperature (°C) | Specific Conductance ($\mu$S/cm) | Dissolved Oxygen (mg/L) | pH |
|---|---|---|---|---|
| December 2000 | 10.24 | 644 | 2.34 | 7.99 |
| June 2001 | 29.3 | 522 | - | 9.60 |
| August 2001 | 33.1 | 521 | 4.02 | 8.01 |
| November 2001 | 11.1 | 492 | 4.88 | 8.35 |
| February 2002 | 12.4 | 450 | 6.4 | 9.07 |
| May 2002 | 27.26 | 447 | 5.4 | 8.98 |

***Table 6.*** *Field parameters for Sevenmile Canyon Boundary Spring water.*

| Date of Sample | Water Temperature (°C) | Specific Conductance ($\mu$S/cm) | Dissolved Oxygen (mg/L) | pH |
|---|---|---|---|---|
| December 2000 | 4.83 | 232 | 3.49 | 7.24 |
| June 2001 | 22.1 | 234 | - | 7.95 |
| August 2001 | 24.56 | 229 | 5.81 | 7.86 |
| November 2001 | 7.2 | 186 | 8.3 | 8.24 |
| February 2002 | 3.1 | 537 (suspect value) | 5.16 | 8.35 |
| May 2002 | 10.24 | 218 | 5.25 | 8.07 |

*Table 7. Field parameters for water from Sleepy Hollow and Willow Springs, collected by the National Park Service.*

| | Date | Temperature °C | pH | Specific Conductance $\mu$S/cm |
|---|---|---|---|---|
| Sleepy Hollow Spring | 03-May-85 | 13.9 | 6.3 | 572 |
| | 23-Jan-86 | 13 | - | 530 |
| | 13-May-87 | 15.8 | 7.5 | 566 |
| | 23-Aug-87 | 19.9 | 7.7 | 597 |
| | 10-May-88 | 11.2 | 6.3 | 567 |
| | 18-Aug-88 | 34.6 | 7.65 | 413 |
| | 15-May-89 | 17.3 | 7.6 | 605 |
| | 10-Aug-89 | 21.6 | 7.45 | 362 |
| | 03-May-90 | 21.4 | 7.66 | 633 |
| Willow Spring | | | | |
| | 03-Jan-85 | 2.6 | - | 546 |
| | 01-May-85 | 15.8 | 6.65 | 221 |
| | 26-Aug-85 | 21.6 | 6.7 | 274 |
| | 04-Jun-87 | 17.65 | 7.55 | 266 |
| | 24-Aug-87 | 21.75 | 7.75 | 250 |
| | 10-May-88 | 13.25 | 6.75 | 265 |
| | 19-Aug-88 | 21.7 | 7.1 | 285 |
| | 14-May-89 | 14.3 | 8.1 | 198 |
| | 11-Aug-89 | 22.4 | 7.5 | 199 |
| | 25-Apr-90 | 13.6 | 8.1 | 228 |

***Table 8.*** *Chemistry of Courthouse Wash Boundary Spring water (Laboratory: Utah State Department of Health, Division of Epidemeology and Laboratory Services).*

| Date of Sample | TDS @ 180°C (mg/L) | Calcium, dissolved (mg/L as Ca) | Magnesium, dissolved (mg/L as Mg) | Sodium, dissolved (mg/L as Na) | Potassium, dissolved (mg/L as K) | Chloride, dissolved (mg/L as Cl) | Sulfate, dissolved (mg/L as $SO_4$) | Fluoride, dissolved (mg/L as F) | Total alkalinity (mg/L as $CaCO_3$) | Carbon dioxide (mg/L as $CO_2$) | Total hardness (mg/L as $CaCO_3$) | Bicarbonate (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| June-2001 | 175.1 | 41.5 | 17.4 | - | - | 4.7 | 80.1 | 0.28 | 202 | 2 | 175.1 | 246 |
| September-2001 | 274 | 32.3 | 15.3 | 60.2 | 2.81 | 4.44 | 63.9 | 0.27 | 162 | 2 | 143.5 | 197 |
| February-2002 | 248 | 37.9 | 20.9 | 59.1 | 3.28 | 5.26 | 90.4 | - | 203 | 2 | 180.6 | 248 |

***Table 9.*** *Chemistry of Sevenmile Canyon Boundary Spring water (Laboratory: Utah State Department of Health, Division of Epidemeology and Laboratory Services).*

| Date of Sample | TDS @ 180°C (mg/L) | Calcium, dissolved (mg/L as Ca) | Magnesium, dissolved (mg/L as Mg) | Sodium, dissolved (mg/L as Na) | Potassium, dissolved (mg/L as K) | Chloride, dissolved (mg/L as Cl) | Sulfate, dissolved (mg/L as $SO_4$) | Fluoride, dissolved (mg/L as F) | Total alkalinity (mg/L as $CaCO_3$) | Carbon dioxide (mg/L as $CO_2$) | Total hardness (mg/L as $CaCO_3$) | Bicarbonate (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| June-2001 | 134 | 36.8 | 4.2 | - | - | <3 | <20 | 0.107 | 99 | 2 | 109.1 | 121 |
| September-2001 | 152 | 42.6 | 4.49 | 3.8 | 1.21 | <3 | <20 | 0.114 | 114 | 2 | 124.8 | 139 |
| February-2002 | 76 | 36.6 | 3.99 | 3.72 | 1.31 | <3 | <20.0 | - | 102 | 2 | 107.7 | 125 |

***Table 10.*** *Scanline data for sample sites in the study area. See text for discussion.*

| Sample Number and Location[1] | Joint Set[2] | Average Orientation | Average Length in meters (number of observations) | Average Spacing in meters (number of observations) |
|---|---|---|---|---|
| S1 | Northwest | 331, 76 | 4.7 + 1.9 (11) | 3.5 + 1.2 (10) |
| Courthouse Wash Boundary | Northeast | 73, 80 | 3.3 (2) | 4.4 (1) |
| Spring | Crossbed Surfaces | 322, 12 | 1.6 + 0.2 (15) | 0.04 + 0.01 (12) |
| S2 | Northwest | 311, 82 | 19 + 7.2 (5) | 11.7 + 2.4 (4) |
| Cedar Point | Northeast | 195, 81 | 9.7 + 2.6 (10) | 4.5 + 1.5 (9) |
| S3 | Northwest | 319, 81 | 8.3 + 4.8 (5) | 8.7 + 5.6 (4) |
| Above Sevenmile Canyon | Northeast | 234, 76 | 8.5 + 3.3 (6) | 7.4 + 2.2 (5) |
| Boundary Spring | Crossbed Surfaces | 290, 10 | 9.4 + 3.3 (8) | 0.4 + 0.1 (7) |
| | Northwest | 323, 79 | 9.0 + 2.5 (21) | 6.5 + 1.6 (18) |
| Combined Data | Northeast | 197, 79 | 8.6 + 1.8 (18) | 5.7 + 1.2 (14) |
| | Crossbed Surfaces | 298, 10 | 4.3 + 1.2 (23) | 0.2 + 0.05 (19) |

Notes

1. See plate 1 for locations.
2. Strike and dip of joints is given in right-hand-rule/azimuth notation. In azimuth notation, the compass is divided into 360 degrees: 0° and 360°are both North, 90° is East, 180° is South, and 270° is West. In right-hand rule notation, the strike is reported as the compass reading when looking in the strike direction such that bedding dips down to the right. The strike of a planar feature is the direction of the line of intersection between a horizontal plane and the feature. The dip of a planar feature is the acute angle between the feature and a horizontal plane, measured in a vertical plane with values from 0 to 90 degrees increasing downward.

*Table 11. Summary statistics for spring discharge data.*

| | Courthouse Wash Boundary Spring | Sevenmile Canyon Boundary Spring | Sleepy Hollow Spring | Poison Ivy Spring |
|---|---|---|---|---|
| Number of Measurements | 14 | 16 | 15 | 14 |
| Range (gpm) | 8.06 | 4.0 | 3.86 | 2.1 |
| Minimum (gpm) | 8.66 | 6.57 | 6.16 | 2.23 |
| Maximum (gpm) | 16.72 | 10.57 | 10.02 | 4.33 |
| Mean | 12.79 | 8.23 | 7.83 | 3.36 |
| Standard Error | 0.59 | 0.25 | 0.25 | 0.16 |
| Median | 13.12 | 8.26 | 7.87 | 3.51 |
| Standard Deviation | 2.27 | 1.01 | 1.07 | 0.62 |
| Variance | 5.13 | 1.03 | 1.14 | 0.39 |
| Kurtosis | -0.14 | 0.73 | -0.22 | -0.79 |
| Skewness | -0.41 | 0.52 | 0.17 | -0.39 |

***Table 12.** Hydrologic parameters for Courthouse Wash Boundary Spring used in the water-budget calculations.*

| Parameter | Range |
|---|---|
| Spring Discharge | 8.66 to 16.72 gallons per minute |
| Recharge Rate | 0.0225 to 0.0525 feet per year |

***Table 13.** Sensitivity analysis of water budget calculation for Courthouse Wash Boundary Spring using ranges of values in table 12. Values in italics are recharge-area estimates using various combinations of recharge rate and spring flow (boldface numbers).*

| | | Recharge Rate (in/yr) | |
|---|---|---|---|
| Spring Discharge (gpm) | **0.27** | **0.46** | **0.63** |
| **16.72** | *1.9* | *1.05* | *0.8* |
| **8.66** | *0.97* | *0.55* | *0.42* |

***Table 14.** Hydrologic parameters for Courthouse Wash Boundary Spring used in the travel-time calculations.*

| Parameter | Range |
|---|---|
| Spring Discharge | 8.66 to 16.72 gallons per minute |
| Aquifer Thickness | 40 to 120 feet |
| Effective Porosity | 15 to 25 percent |

***Table 15.** Results of a sensitivity analysis of travel-time calculations for Courthouse Wash Boundary Spring using the ranges of values in table 14.*

| | | Aquifer Thickness (feet) | | | Effective Porosity | | |
|---|---|---|---|---|---|---|---|
| | | 120 | 80 | 40 | 0.25 | 0.2 | 0.15 |
| Spring Discharge (gpm) | 16.72 | 0.17 | 0.26 | 0.09 | 0.21 | 0.26 | 0.35 |
| | 8.66 | 0.52 | 0.14 | 0.27 | 0.11 | 0.14 | 0.15 |

***Table 16***. *Comparison of recharge-area estimates from three alternative methods. See text for explanation of methods.*

| | Water Budget (Equation 1) | Catchment Area (Todd, 1980, p. 49) | Travel Time (Equation 2) |
|---|---|---|---|
| Courthouse Wash Boundary Spring | 1.05 $mi^2$<br>2.7 $km^2$ | 1.2 $mi^2$<br>3.1 $km^2$ | 0.26 $mi^2$<br>0.7 $km^2$ |
| Sevenmile Canyon Boundary Spring | 0.67 $mi^2$<br>1.7 $km^2$ | 0.73 $mi^2$<br>1.9 $km^2$ | 0.17 $mi^2$<br>0.4 $km^2$ |
| Sleepy Hollow Spring | 0.64 $mi^2$<br>1.7 $km^2$ | 0.66 $mi^2$<br>1.7 $km^2$ | 0.16 $mi^2$<br>0.4 $km^2$ |
| Poison Ivy Spring | 0.35 $mi^2$<br>0.9 $km^2$ | 0.34 $mi^2$<br>0.9 $km^2$ | 0.09 $mi^2$<br>0.2 $km^2$ |

## FIGURE CAPTIONS

Figure 1. Views of Courthouse Wash. A. View downstream (southeast) from eastern boundary of study area. B. View upstream (northwest) of confluence area of lower Sevenmile Canyon and Courthouse Wash.

Figure 2. Views of the springs focused on in this study. A. Courthouse Wash Boundary Spring. Dark areas on bedrock just above wash show ground water issuing from joints in the upper part of the Moab Member of the Curtis Formation (Jctm). Qao is older alluvium. B. Sevenmile Canyon Boundary Spring. The area from which the spring issues is in shadows. Jctm is Moab Member of Curtis Formation; Jes is Slick Rock Member of Entrada Sandstone.

Figure 3. Physiographic and hydrologic features of the study area.

Figure 4. Regional tectonic setting of the study area, showing major features including salt anticlines, Paradox basin, Uncompahgre uplift and fault, and Tertiary intrusions (modified from Doelling, 1988).

Figure 5. Stratigraphic column for the study area, from Doelling (2001). Not all units shown in the stratigraphic column are present on figure 6.

Figure 6. Generalized geologic map of the study area, after Doelling (2001).

Figure 7. Prominent geologic units and structures in the study area. A. View west to cliff on north side of upper Sevenmile Canyon, west of US191. Cliff is about 800 feet (244 m) high. Jk – Kayenta Formation; Jw – Wingate Sandstone; TRc – Chinle Formation; TRm – Moenkopi Formation; Pc – Cutler Formation. See figure 5 and appendix A for information on rock units. B. Outcrops of Summervile Formation (Js) and Tidwell Member of the Morrison Formation (Jmt) (combined as unit Jsmt on figure 6 and plate 1B), about 100 feet (30 m) southwest of Courthouse Wash Boundary Spring. These units overlie, and form a confining layer above, the Moab Member of the Curtis Formation (not shown). Hammer (circled) is 11 inches (23 cm) long.

Figure 7 (continued). C. Moab Member of Curtis Formation (Jctm) above Slick Rock Member of Entrada Formation (Jes) on north wall of lower Sevenmile Canyon near canyon head. Contact shown by black line. The Moab Member is about 80 feet (24 m) thick here has much greater joint density, and most joints in the Moab Member do not penetrate down into the Slick Rock Member. D. Slick Rock Member of the Entrada Sandstone (Jes) overlying Dewey Bridge Member of the Carmel Formation (Jcd) in

Arches National Park, about 0.25 miles (0.4 km) west of the Arches Highway bridge over Courthouse Wash. Cliff is about 300 feet (91 m) high.

Figure 8. View northwest of the Moab fault (dashed line), about 2 miles (3.2 km) southeast of the southern study-area boundary. The Moab fault juxtaposes densely jointed Moab Member of the Curtis Formation (Jctm) in its hanging wall against Cutler Formation (Pc) in its footwall. Note the normal-drag fold in the Cutler Formation adjacent to the fault. The dense jointing in the Moab Member likely enhances fault-parallel ground-water flow in the subsurface.

Figure 9. Areal distribution of average annual precipitation and location of precipitation gauges (lines of equal precipitation modified from Woodward-Clyde Consultants, 1982).

Figure 10. Hydrographs of Courthouse Wash at Arches Highway and near its confluence with the Colorado River (U.S. Geological Survey, 2002b).

Figure 11. Springs and seeps in Courthouse Wash and lower Sevenmile Canyon. A. Spring and seeps issuing from the contact between the Moab Member of the Curtis Formation (Jctm) and the Slick Rock Member of the Entrada Sandstone (Jes), in an alcove in the south wall of lower Sevenmile Canyon about ¾ mile (1.2 km) west of

Sevenmile Canyon Boundary Spring. B. Sleepy Hollow Spring issuing from the contact between the Moab Member of the Curtis Formation (Jctm) and the Slick Rock Member of the Entrada Sandstone (Jes) and from solution-widened joints along cross-bed boundaries in the Moab Member, in an alcove in the north wall of Courthouse Wash about 1 mile (0.6 km) southeast of Courthouse Wash Boundary Spring.

Figure 12. Instantaneous monthly flow for springs monitored in this study.

Figure 13. Water temperature records for Courthouse Wash Boundary Spring and Sevenmile Canyon Boundary Spring, and mean air temperatures at Park headquarters (National Weather Service, 2002).

Figure 14. Specific conductance and pH of water samples from Sevenmile Canyon Boundary, Courthouse Wash Boundary, Willow, and Sleepy Hollow Springs.

Figure 15. Trilinear diagram depicting geochemical analyses of water samples from Courthouse Wash Boundary Spring.

Figure 16. Trilinear diagram depicting geochemical analyses of water samples from Sevenmile Canyon Boundary Spring.

Figure 17. Ground water seeping from joints in the Moab Member of the Curtis Formation in Willow Spring wash, about 300 feet (91 m) east of its confluence with Courthouse Wash.

Figure 18. Digital orthophotograph of the Courthouse Wash–lower Sevenmile Canyon area. The black line shows top of the Moab Member of the Curtis Formation (Jctm). The northwest-striking joint set is conspicuous as dark striations on Moab Member outcrop. The northeast-striking joint set is less obvious but is visible north of the middle part of lower Sevenmile Canyon. The long, northeast-trending lineaments south of lower Sevenmile Canyon are washes that do not coincide with fracture traces. Image by U.S. Geological Survey, obtained online from Utah AGRC (<http://agrc.utah.gov>).

Figure 19. Equal-area "rose" histograms illustrating data on joint orientations and lengths for sample sites in table 10. Figure 6 and plate 1b show the sample sites, all of which are on the Moab Member of the Curtis Formation. Adjacent to the circle, n = number of samples and d = circle diameter. In the normalized length plots, the circle diameter is proportional to the greatest average joint length. In the relative abundance plots, the circle diameter equals the percent of the total number of joints in the sector

containing the greatest joint abundance. Tick lines are in 10-degree intervals, and joint orientations are grouped into 15-degree sectors. The diagrams are bi-directional; each sector includes joints with strikes 180 degrees apart (parallel strikes but opposite dip directions), and "rose petals" 180 degrees apart have the same length.

Figure 20. Equal-area "rose" histogram illustrating the orientations of deformation bands more than about 100 feet (30 m) east of the Moab fault, including the deformation-band zone crossing the head of lower Sevenmile Canyon shown as a fault on plate 1B. The data are from individual sites throughout the study area, and the "rose-petal" lengths only qualitatively reflect the relative abundances of deformation bands in each orientation sector. See figure 19 caption and table 10 for further explanation of rose histograms.

Figure 21. Views of the Moab fault. A. View to the northwest, showing resistant deformation-band zone (dbz) in sandstone of the Salt Wash Member of the Morrison Formation (Jms), and scaly foliation cut by slip surfaces in the Cutler Formation (Pc). The deformation-band zone likely forms a barrier to cross-fault ground-water flow in the subsurface. About one mile (1.6 km) southeast of the southern study-area boundary. B. View to the northeast of Moab fault juxtaposing sandstone of the Cedar Mountain Formation (Kcm) in the hanging wall against mudstone of the Chinle Formation (TRc) in the footwall. The Moab fault core consists of a 1-foot (0.3 m) thick deformation-band zone (dbz) in Cedar Mountain sandstone and scaly foliation in Cedar Mountain and

Chinle mudstones. The sandstone-mudstone contact is a smooth, slickensided slip surface. Hammer is 11 inches (28 cm) long.

Figure 21 (continued). C. View to the southwest, showing sandstone and mudstone of the Dakota Sandstone (Kd) in the hanging wall juxtaposed against the Wingate Sandstone (Jw) in the footwall. In the fault core, a silica-cemented breccia zone bounded by a slickenside surface (smooth surface) is developed in the Wingate Sandstone. This cemented breccia zone likely forms a barrier to ground-water flow in the subsurface. Hammer (circled) is 11 inches (28 cm) long. D. Closer view of the silica-cemented fault breccia shown in figure 21c. The breccia is bounded on either side by slickensided slip surfaces. Hammer is 11 inches (28 cm) long.

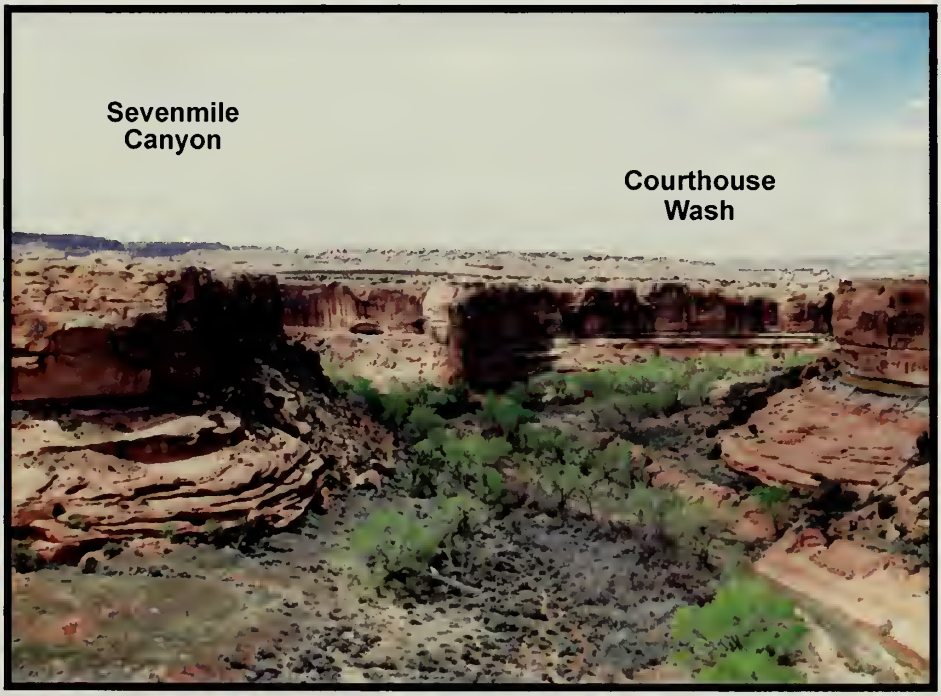
Figure 21 (continued). E. View to the southeast of a road cut along the old Moab highway, near the southern study-area boundary. Sandstone of the Salt Wash Member of the Morrison Formation (Jms) in the hanging wall is densely jointed, and bedding in arkosic sandstone and mudstone of the Cutler Formation (Pc) in the footwall is highly disrupted and cut by slip surfaces. The fault core is composed of a 1-foot (30.5 cm) thick, clay-rich gouge zone (pale band just above hammer) that likely forms a barrier to cross-fault ground-water flow in the subsurface. Hammer is 11 inches (28 cm) long.

Figure 22. Equal-area "rose" histograms illustrating the orientations of structural elements in and adjacent to the Moab fault core. The data are from individual sites throughout the study area, and the "rose-petal" lengths only qualitatively reflect the relative abundances of deformation bands in each orientation sector. See figure 19 and table 10 captions for further explanation of rose histograms.

Figure 23. View southeast of densely jointed Moab Member of the Curtis Formation (Jctm) in the hanging wall of the Moab fault, about 2 miles (3.2 km) southeast of the southern study-area boundary. The dense jointing likely enhances fault-parallel ground-water flow in the subsurface. The footwall is composed of Cutler Formation (Pc).

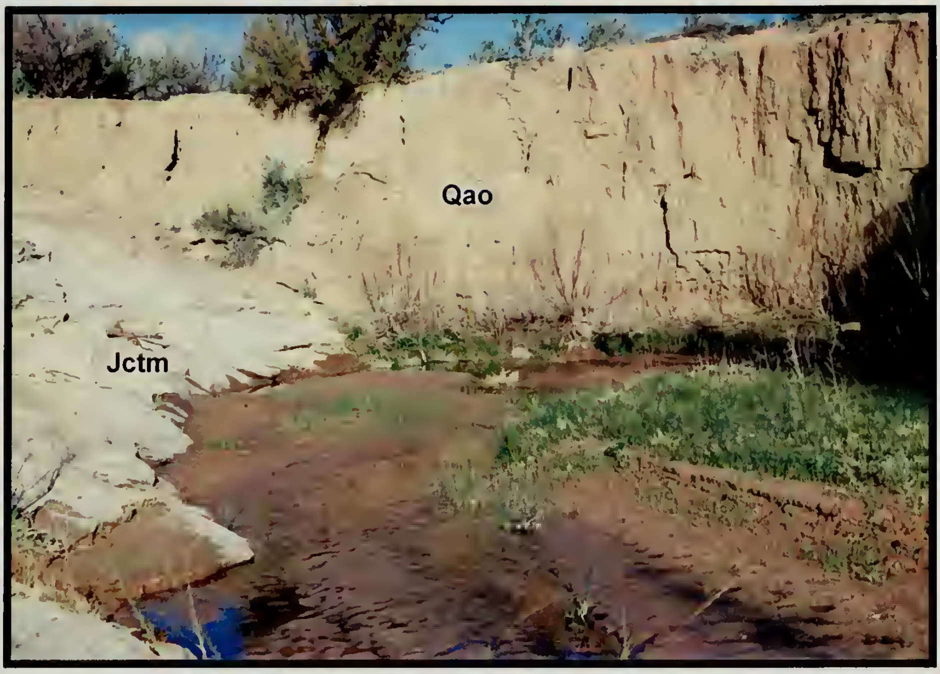
Figure 24. Schematic representation of estimated recharge areas for Courthouse Wash Boundary Spring and the eastern and western spring groups.

*1A*




*1B*

*Figure 1.*




*2A*


*2B*

*Figure 2.*

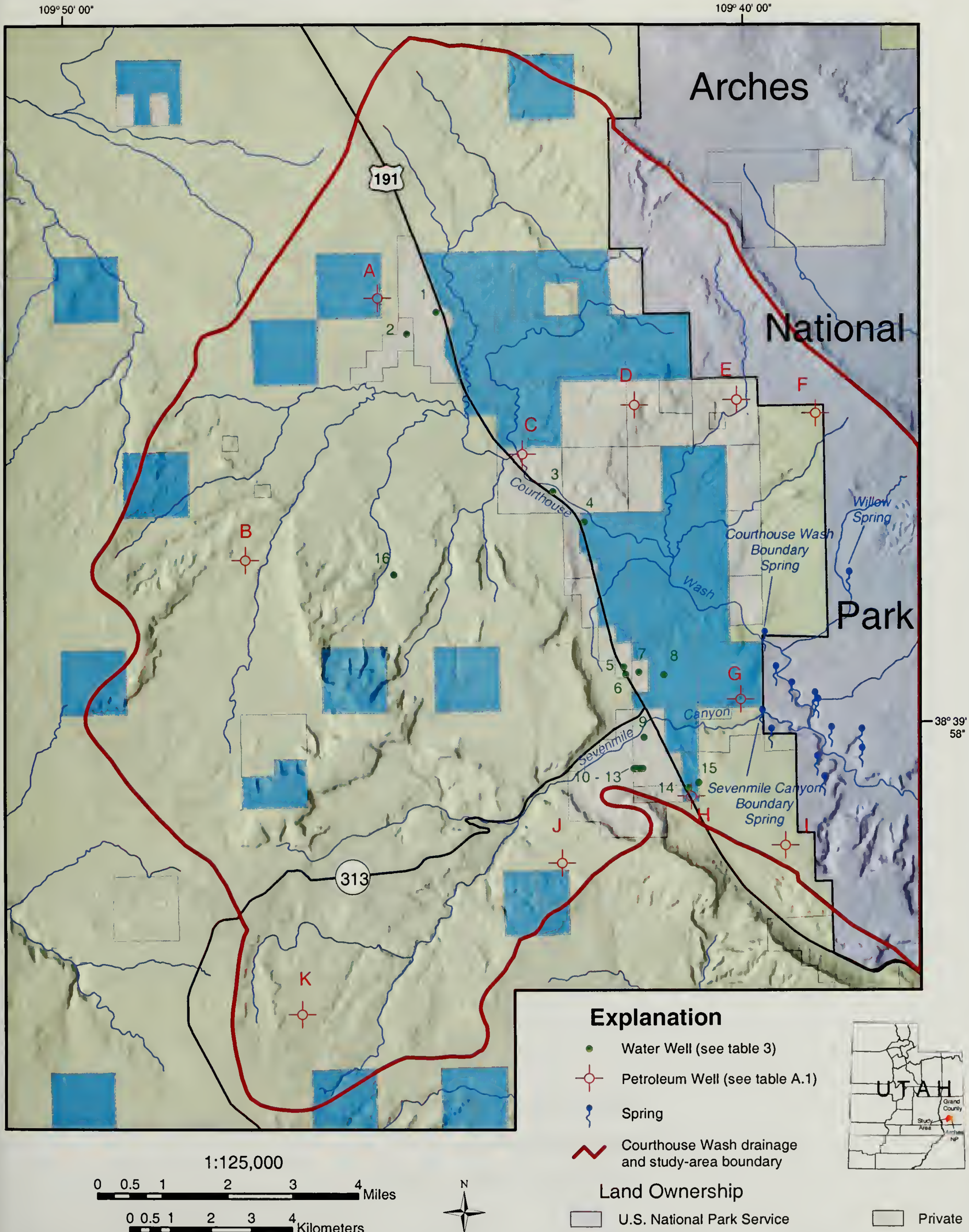



*Figure 3. Physiographic and hydrologic features of the study area. Basemap from U.S. Geological Survey Moab 30' X 60' quadrangle.*

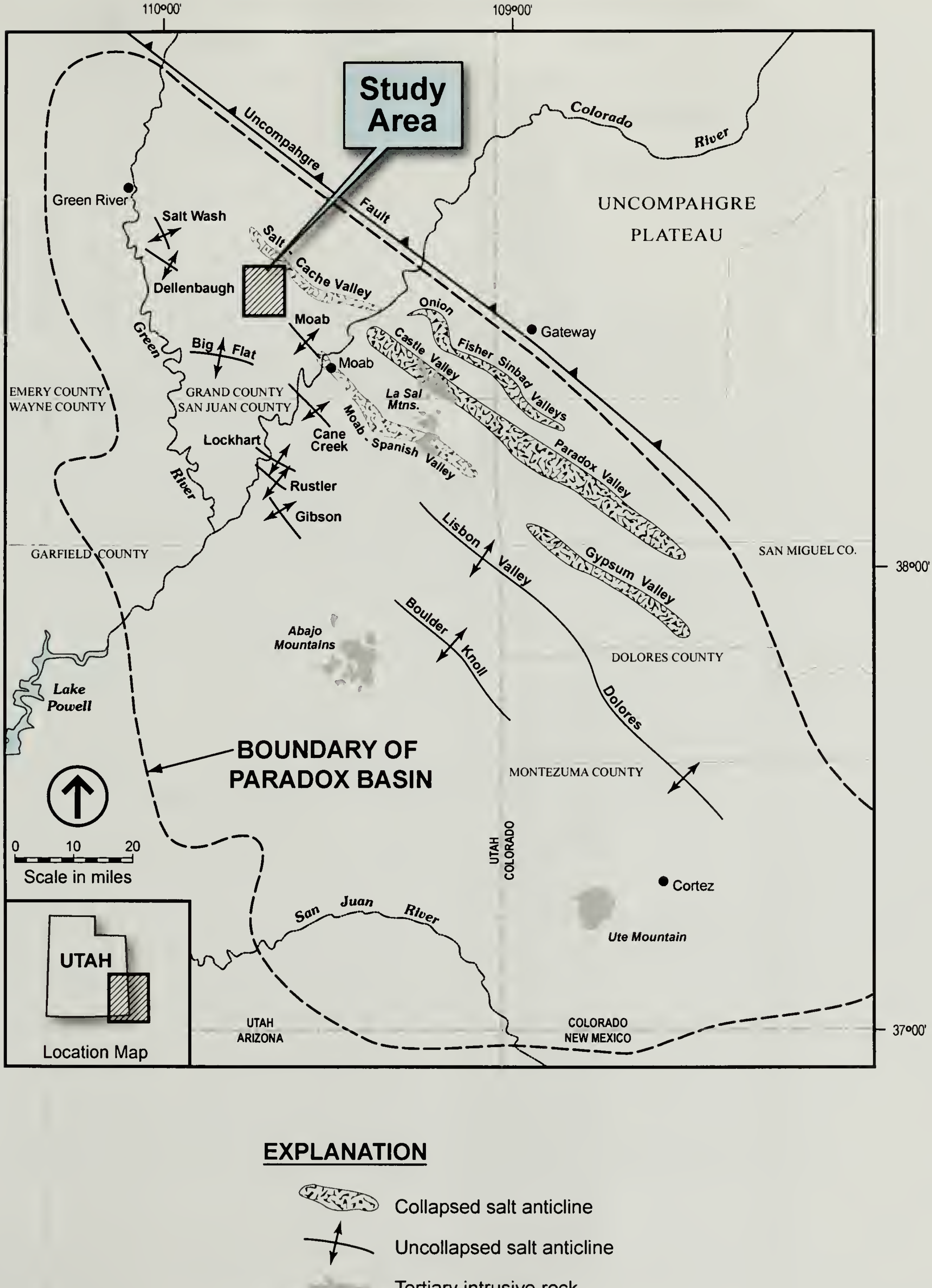



*Figure 4. Regional tectonic setting of the study area, showing major tectonic features including salt anticlines, Paradox basin, Uncompahgre uplift and fault, and Tertiary intrusions (modified from Doelling, 1988).*

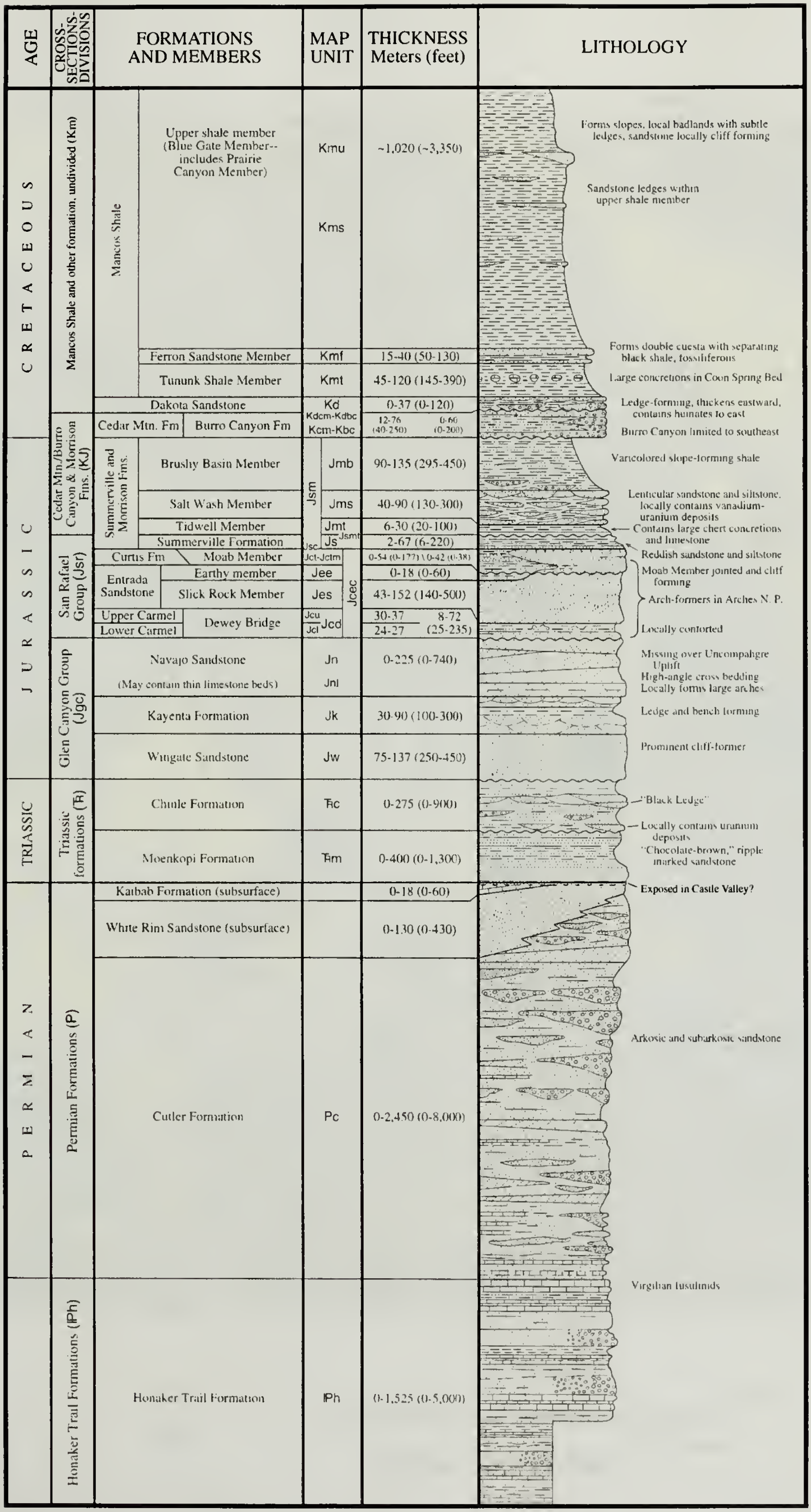



***Figure 5.*** *Stratigraphic column for the study area, from Doelling (2001). Not all units shown in the stratigraphic column are present on figure 6.*

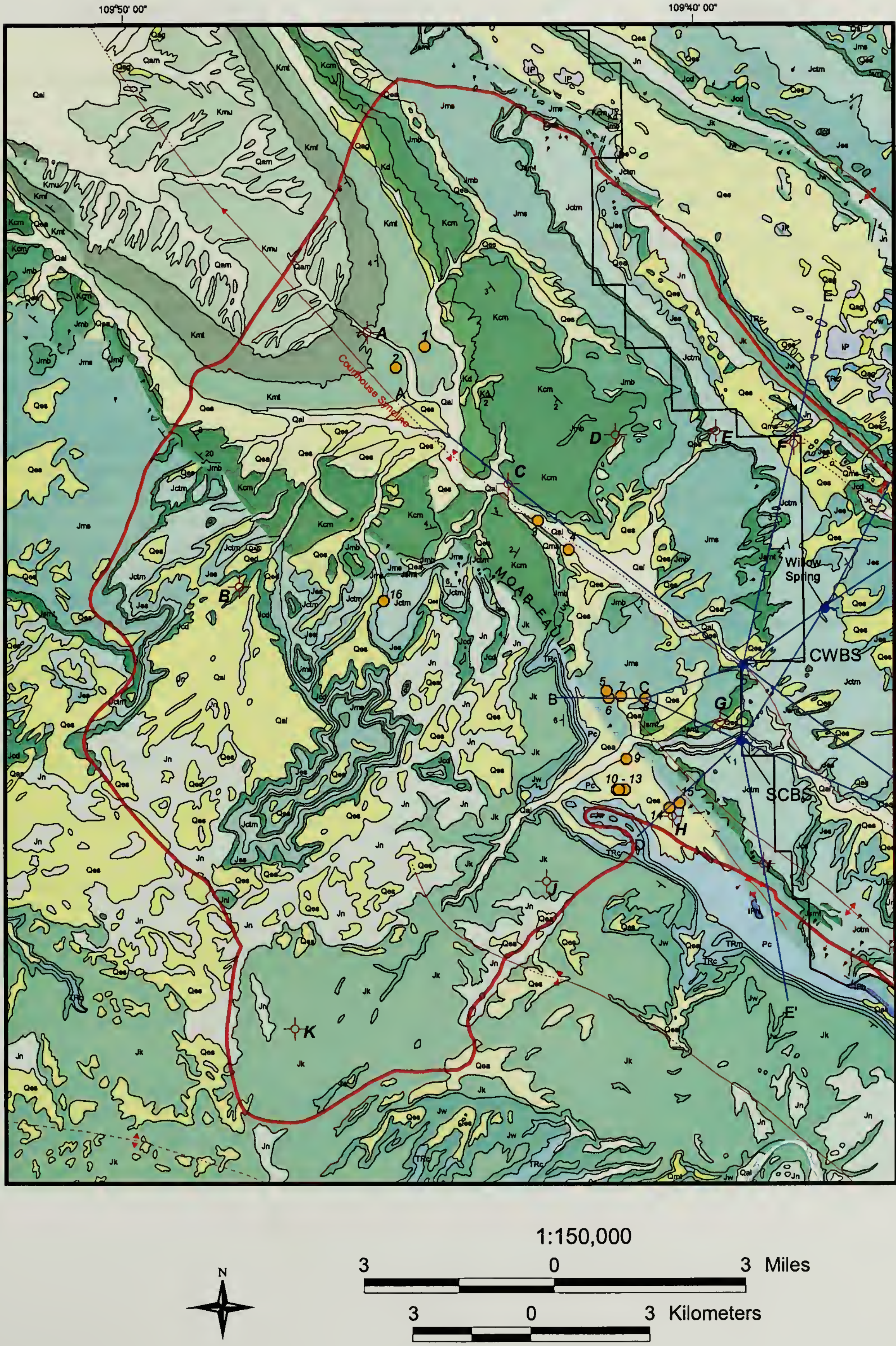



*Figure 6. Generalized geologic map of the study area, after Doelling (2001). CWBS-Courthouse Wash Boundary Spring; SCBS-Sevenmile Canyon Boundary Spring.*

## EXPLANATION

**Map Units – see appendix A for descriptions.**

**Quaternary**
- Qal – Stream alluvium
- Qag – Alluvial gravel
- Qea – Mixed eolian and alluvial deposits
- Qes – Eolian deposits

**Cretaceous**
- Kmu – Upper Shale Member of Mancos Shale
- Kmf – Ferron Sandstone Member of Mancos Shale
- Kmt – Tununk Shale Member of Mancos Shale
- Kd – Dakota Sandstone
- Kcm – Cedar Mountain Formation

**Jurassic**
- Jmb – Brushy Basin Member of Morrison Formation
- Jms – Salt Wash Member of Morrison Formation
- Jsmt – Tidwell Member of Morrison Formation and Summerville Formation, undivided
- Jctm – Moab Member of Curtis Formation
- Jes – Slick Rock Member of Entrada Sandstone
- Jcd – Dewey Bridge Member of Carmel Formation
- Jn – Navajo Sandstone
- Jk – Kayenta Formation
- Jw – Wingate Sandstone

**Triassic**
- TRc – Chinle Formation
- TRm – Moenkopi Formation

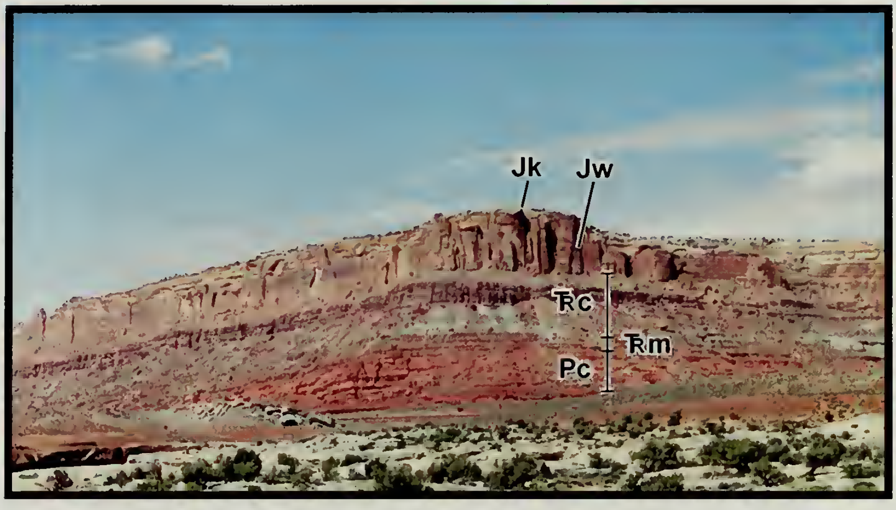
**Permian**
- Pc – Cutler Formation

**Pennsylvanian**
- IPh – Honaker Trail Formation

## SYMBOLS

- Contact – dashed where location inferred
- Fault – dashed where location inferred, dotted where concealed; ball and bar on downthrown side
- Anticline – dashed where location inferred; arrow shows direction of plunge
- Syncline – dashed where location inferred; arrow shows direction of plunge
- 5 Strike and dip of bedding
- Water well – see table 3
- Spring
- Petroleum well – plugged and abandoned; see table A.1
- **B-B'** Cross section – see plate 2
- Arches National Park boundary
- Study area boundary

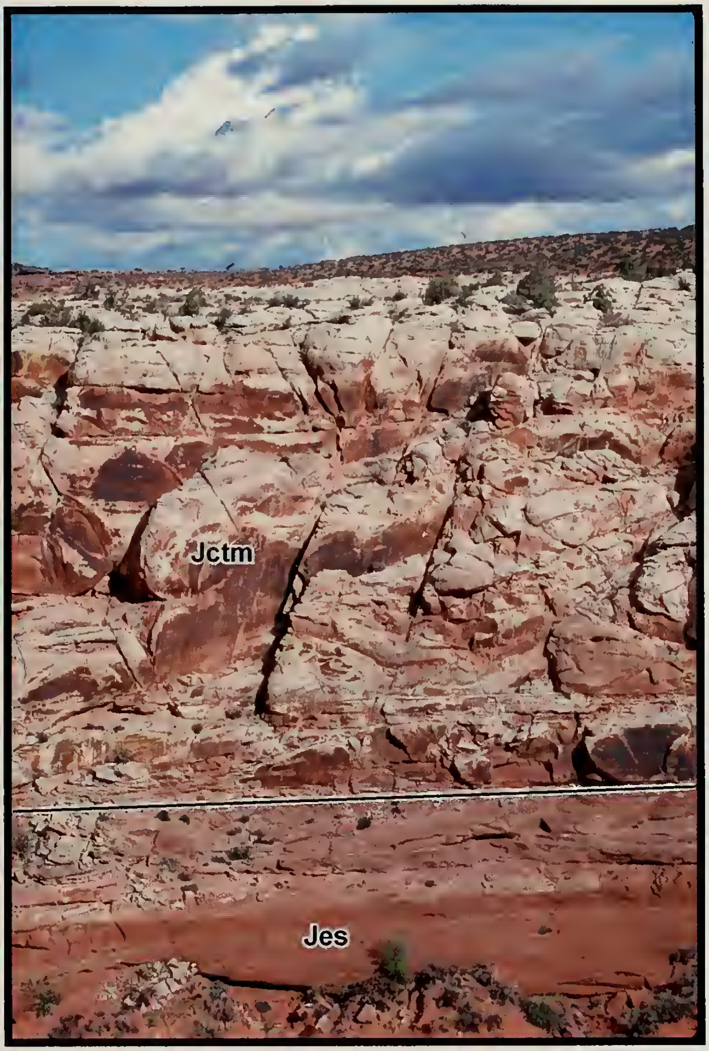
*Figure 6.* *Explanation.*




*7A*


*7B*

*Figure 7.*




7C


7D

*Figure 7 (continued).*

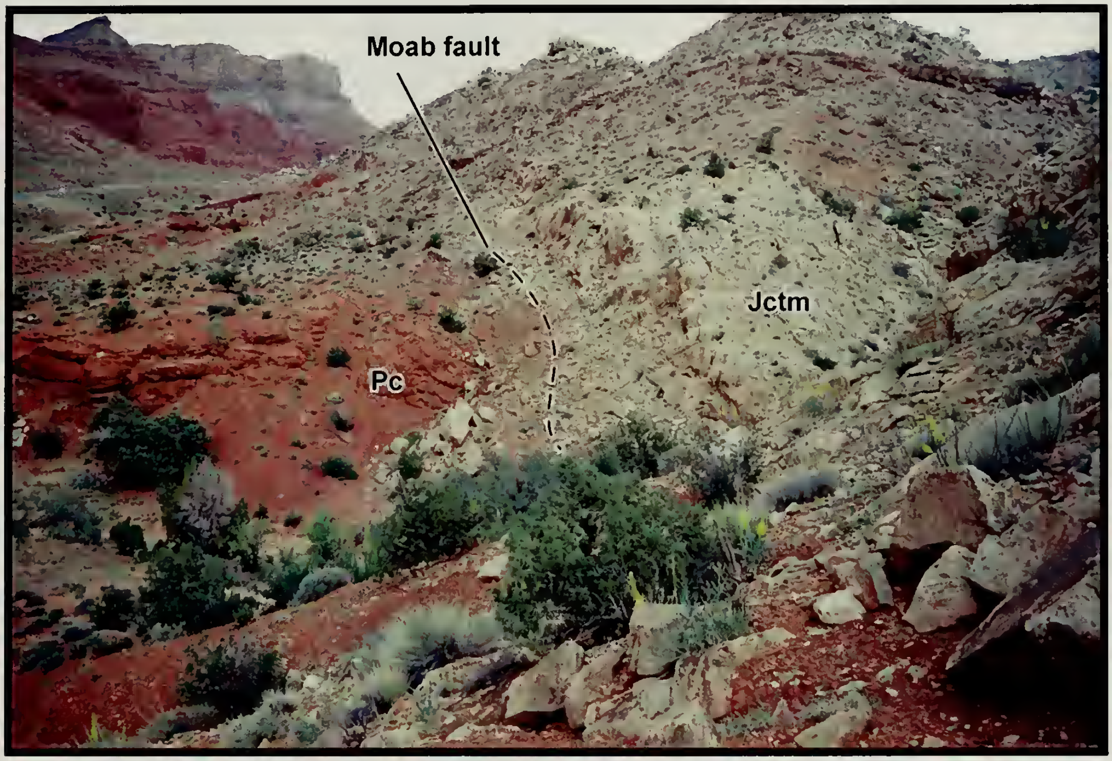



*Figure 8.*

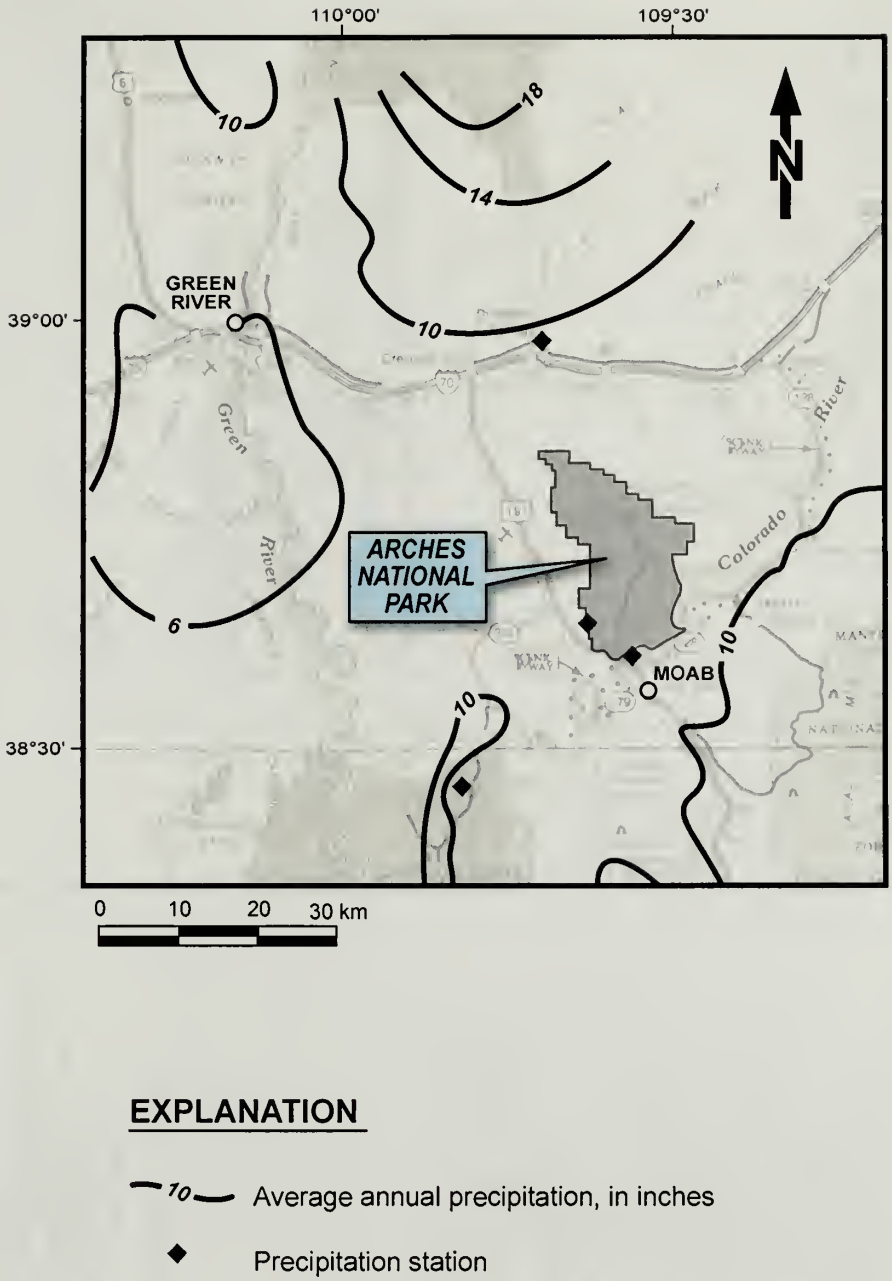



***Figure 9.*** *Areal distribution of average annual precipitation and location of precipitation gauges (lines of equal precipitation modified from Woodward – Clyde Consultants, 1982).*

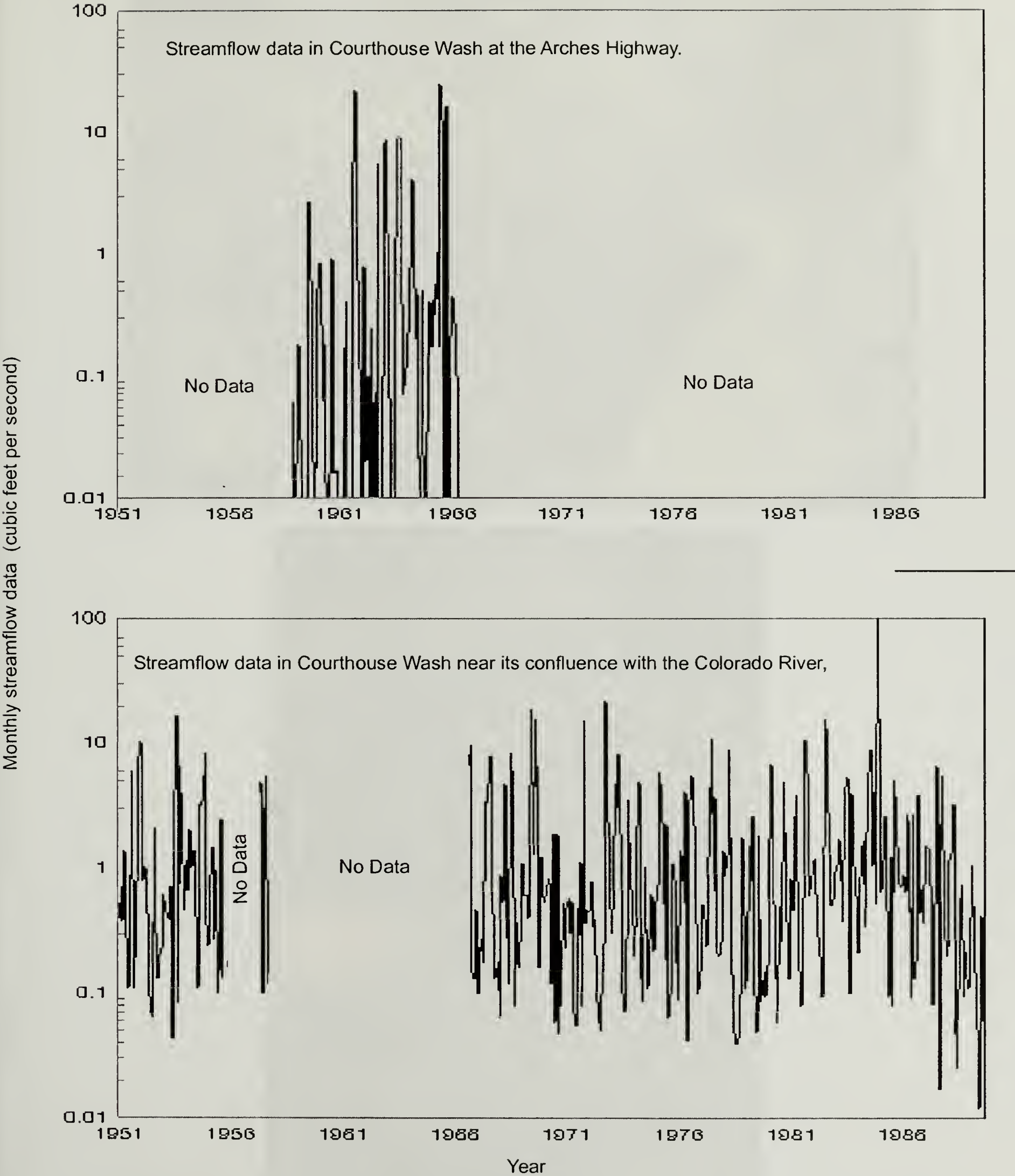
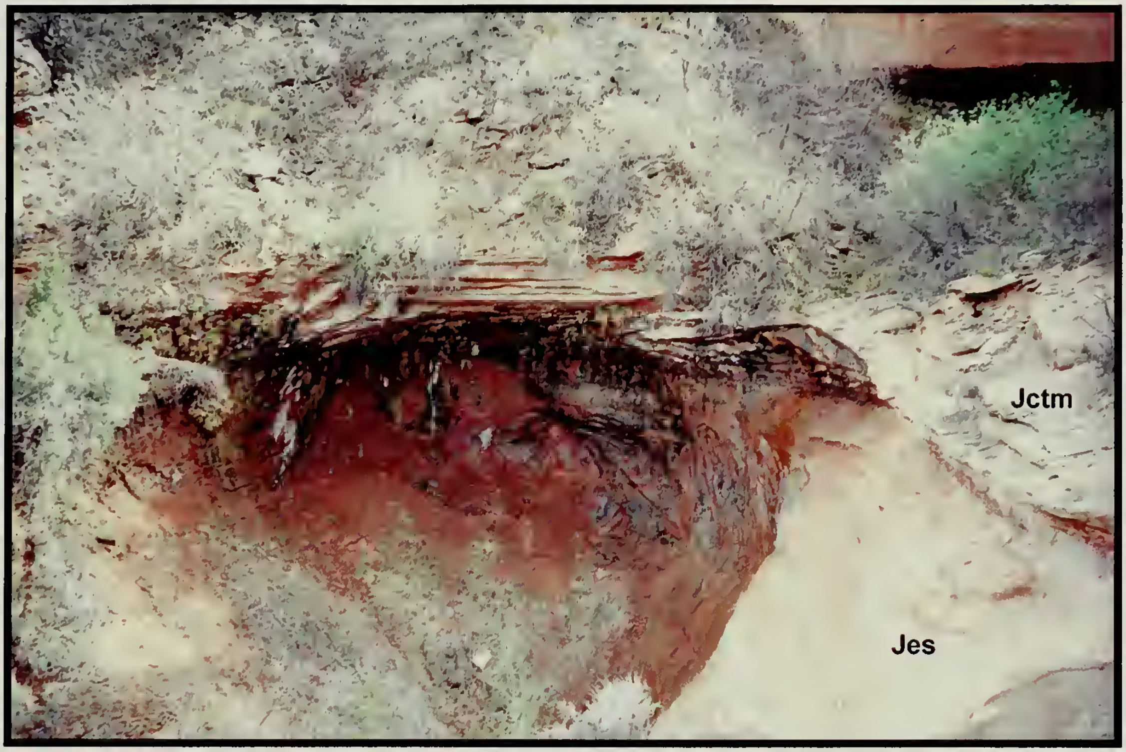
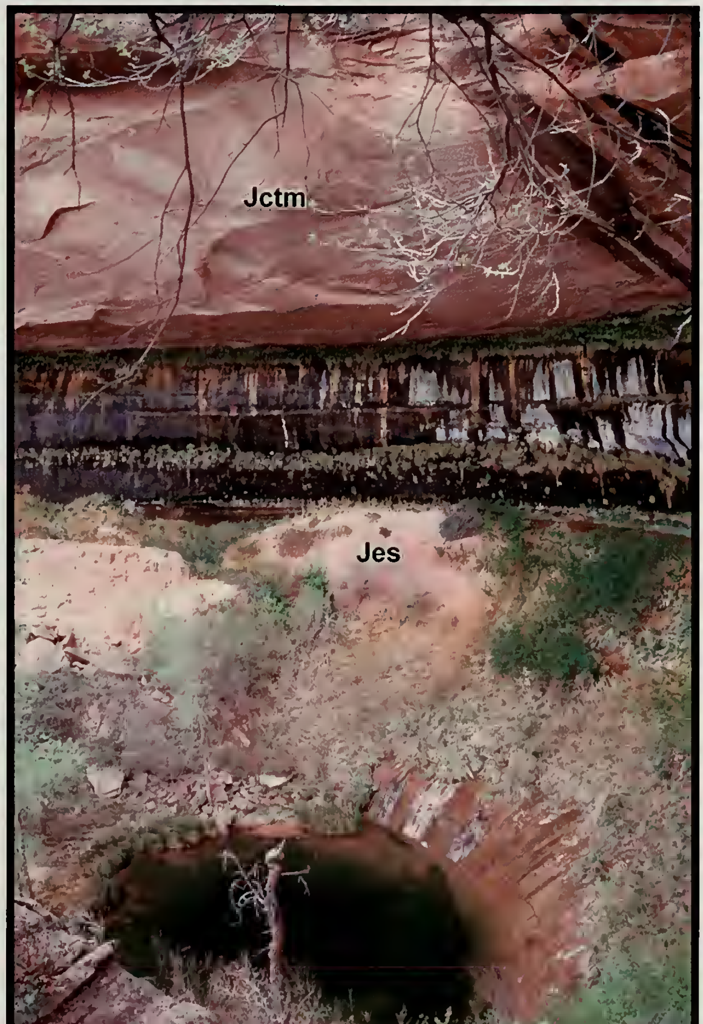



***Figure 10.*** *Hydrographics of Courthouse Wash at Arches Highway and near its confluence with the Colorado River (U.S. Geological Survey [2002b]).*




*11A*




*11B*

*Figure 11.*

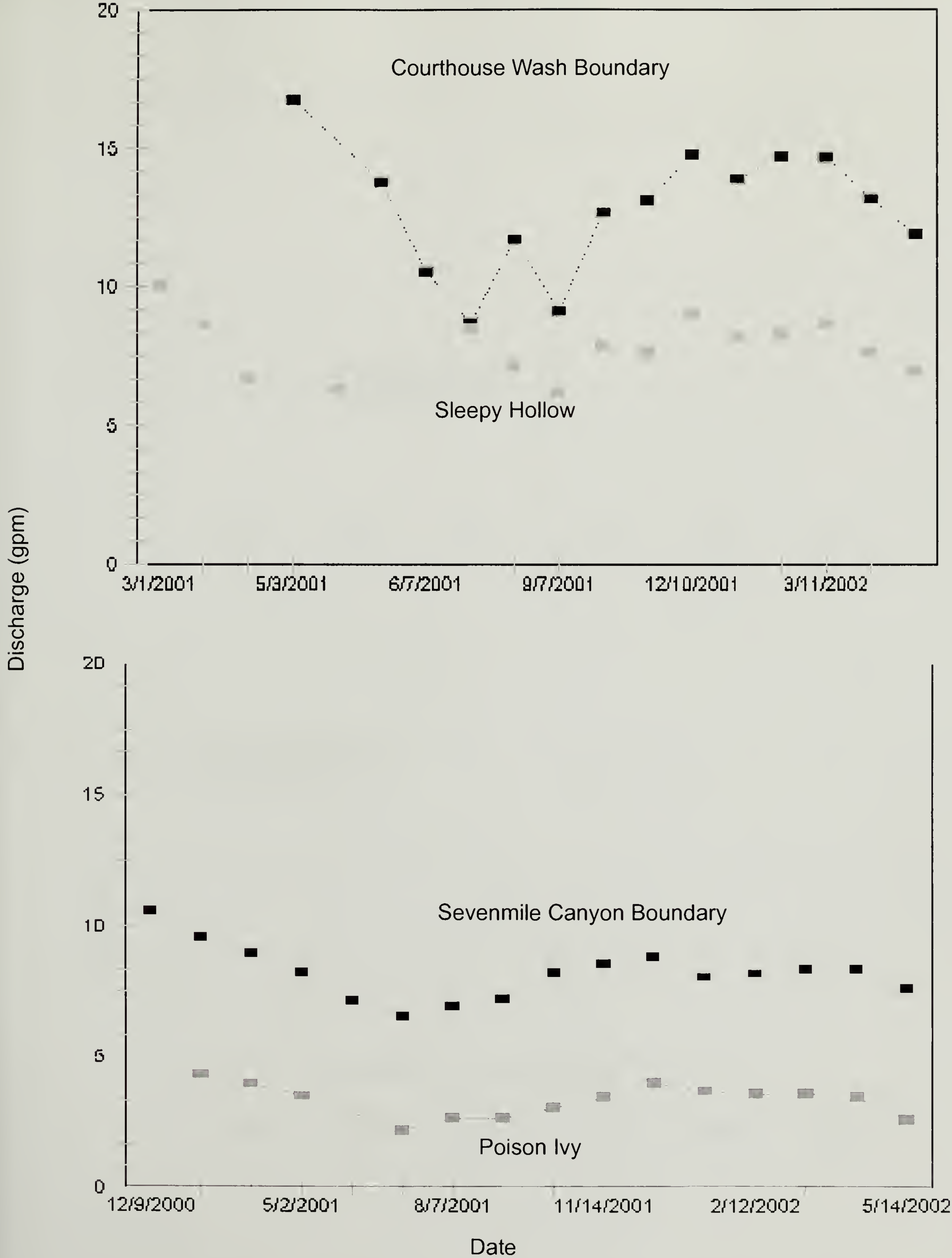



***Figure 12****. Instantaneous monthly flow for springs monitored for this study (Based on unpublished National Park Service data).*

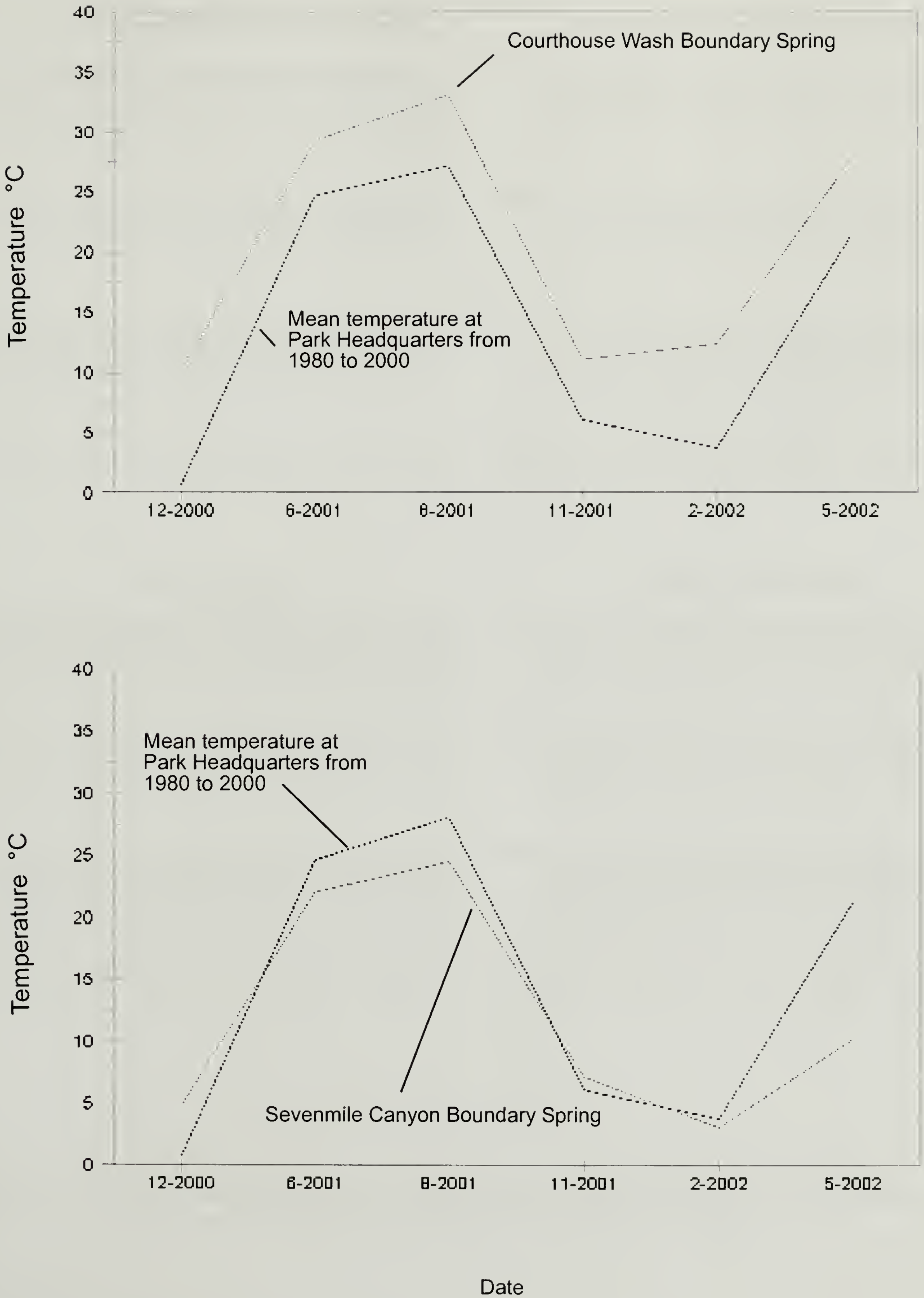



***Figure 13.*** *Water temperature records for Courthouse Wash Boundary Spring and Sevenmile Canyon Boundary Spring and mean air temperature at Arches National Park headquarters (National Weather Service, 2002).*

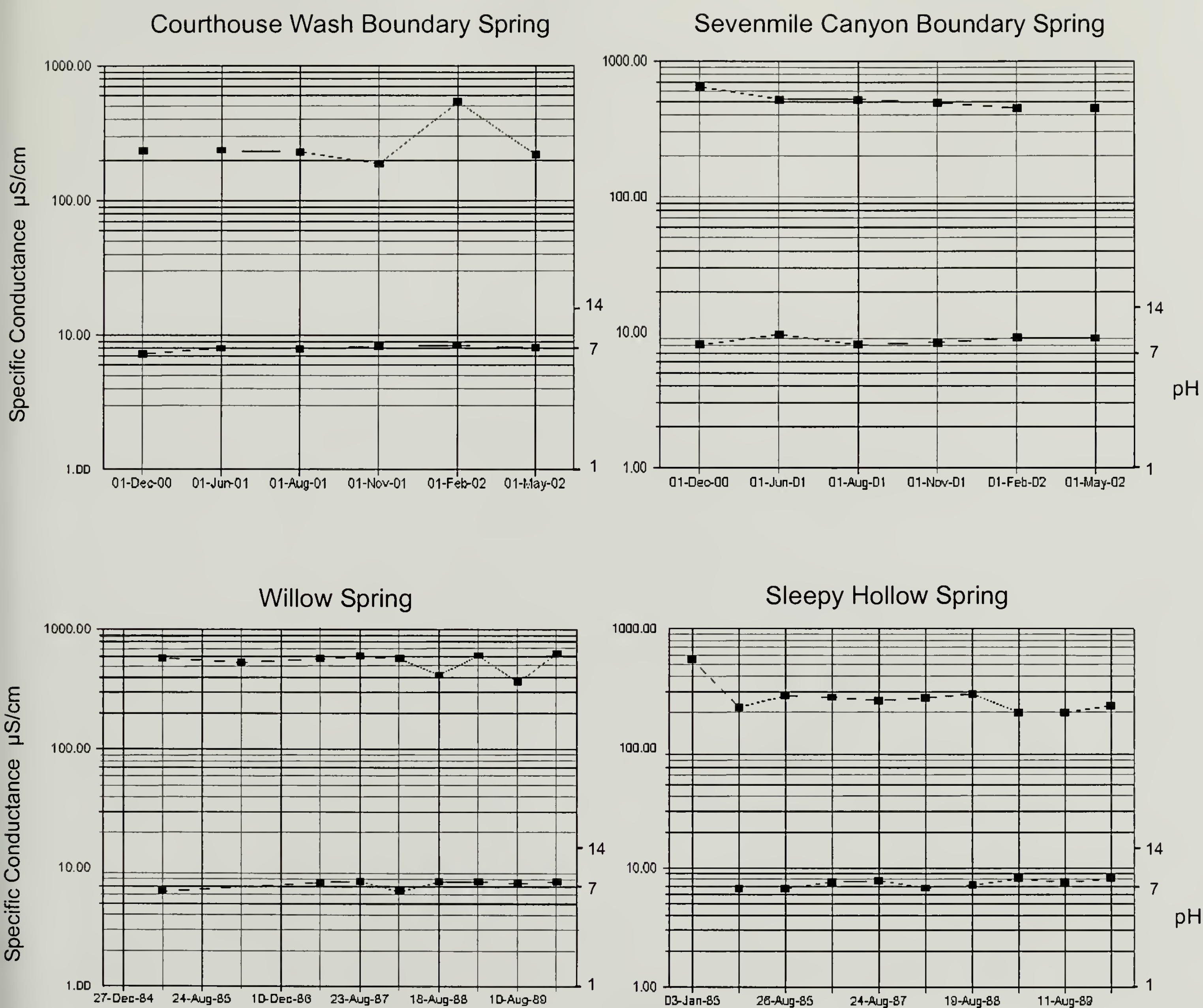



*__Figure 14.__ Specific conductance and pH of water samples from Sevenmile Canyon Boundary, Courthouse Wash Boundary, Willow, and Sleepy Hollow springs.*

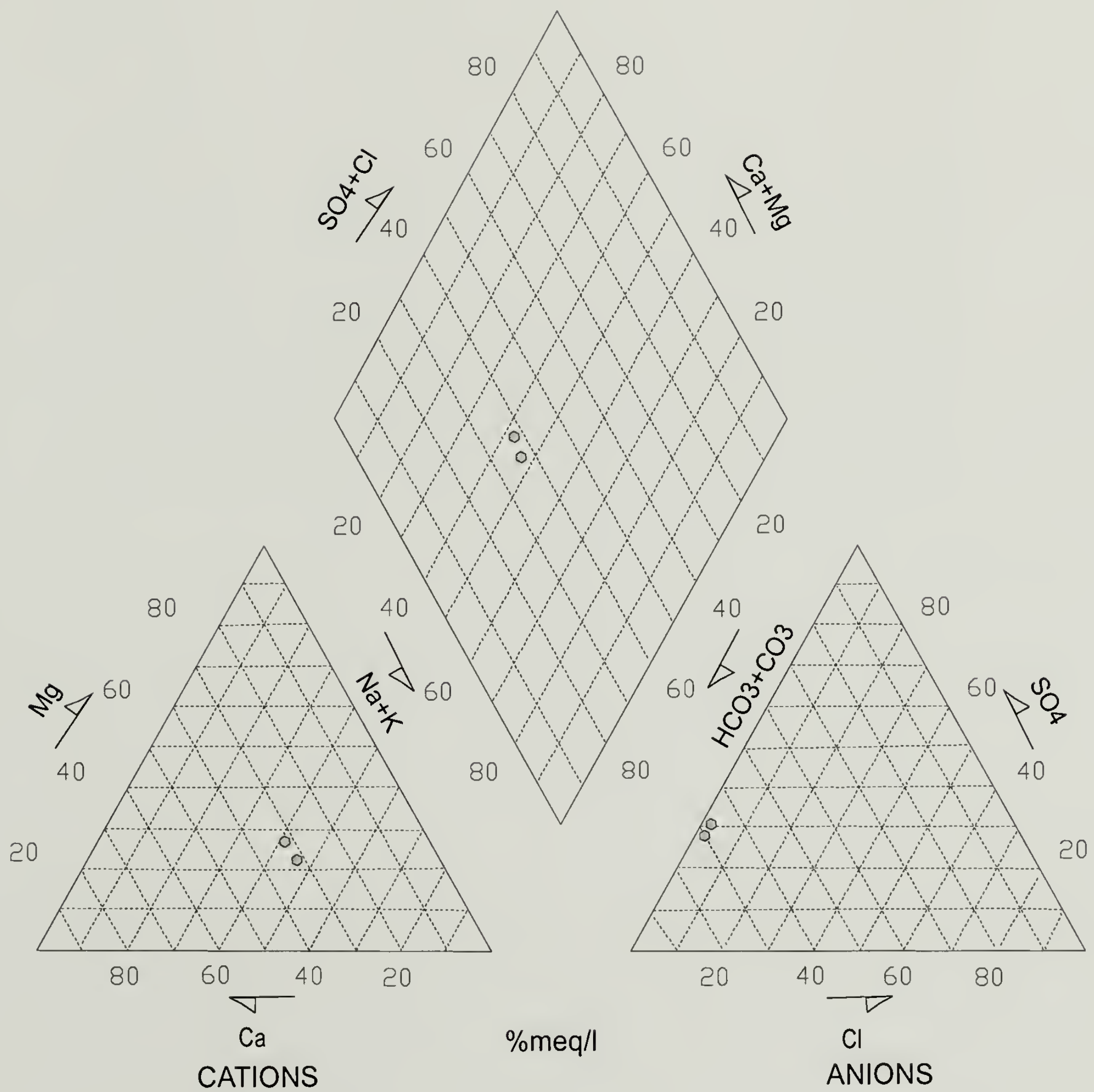



*Figure 15. Trilinear diagram depicting geochemical analyses of water samples from Courthouse Wash Boundary Spring.*

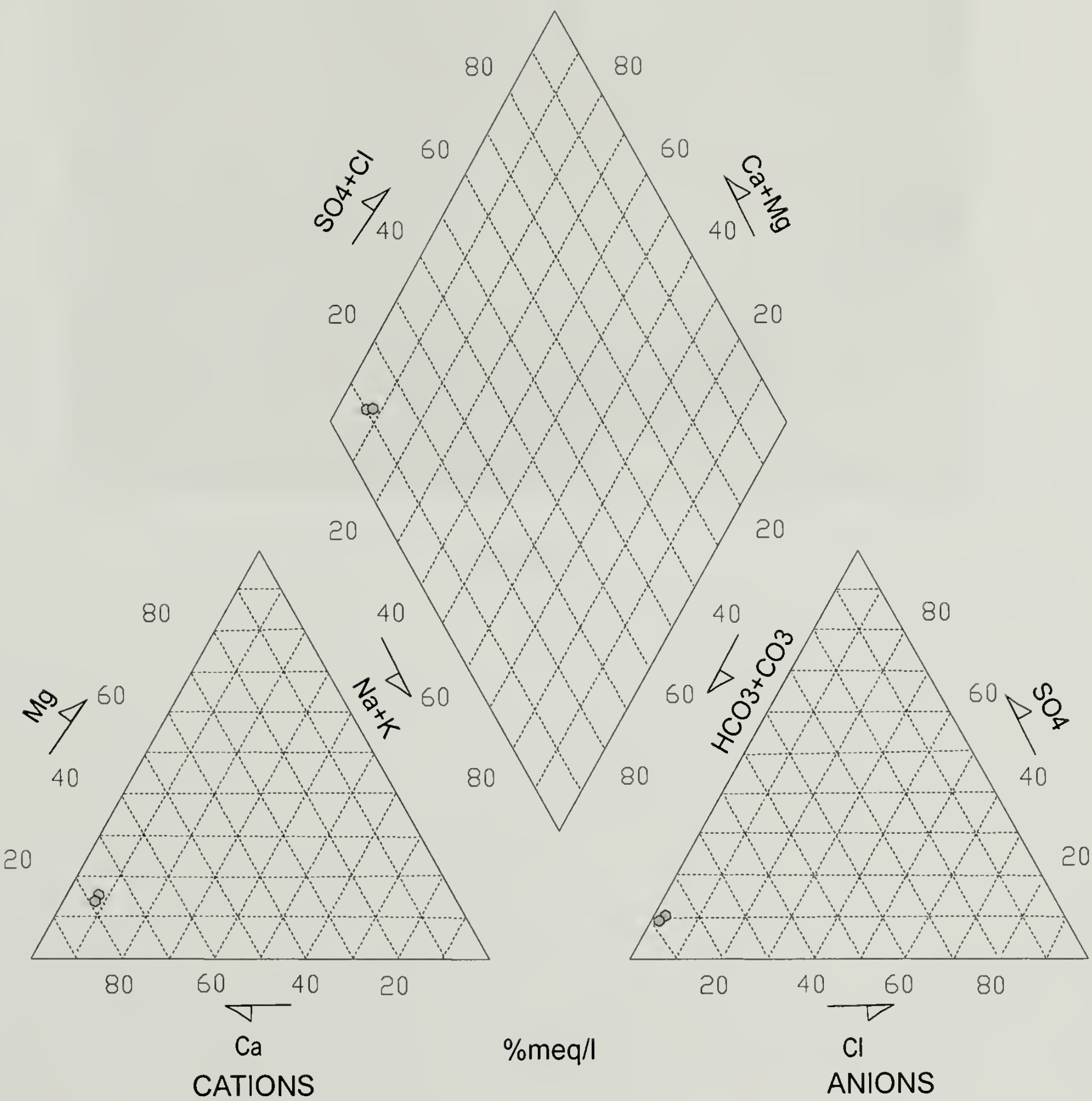



***Figure 16.*** *Trilinear diagram depicting geochemical analyses of water samples from Sevenmile Canyon Boundary Spring.*

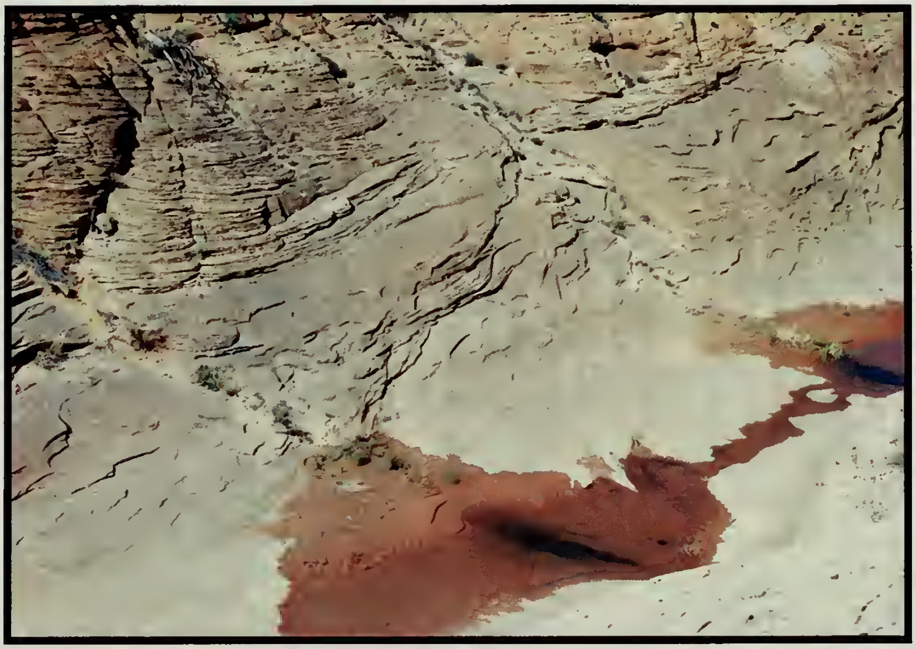


*Figure 17.*

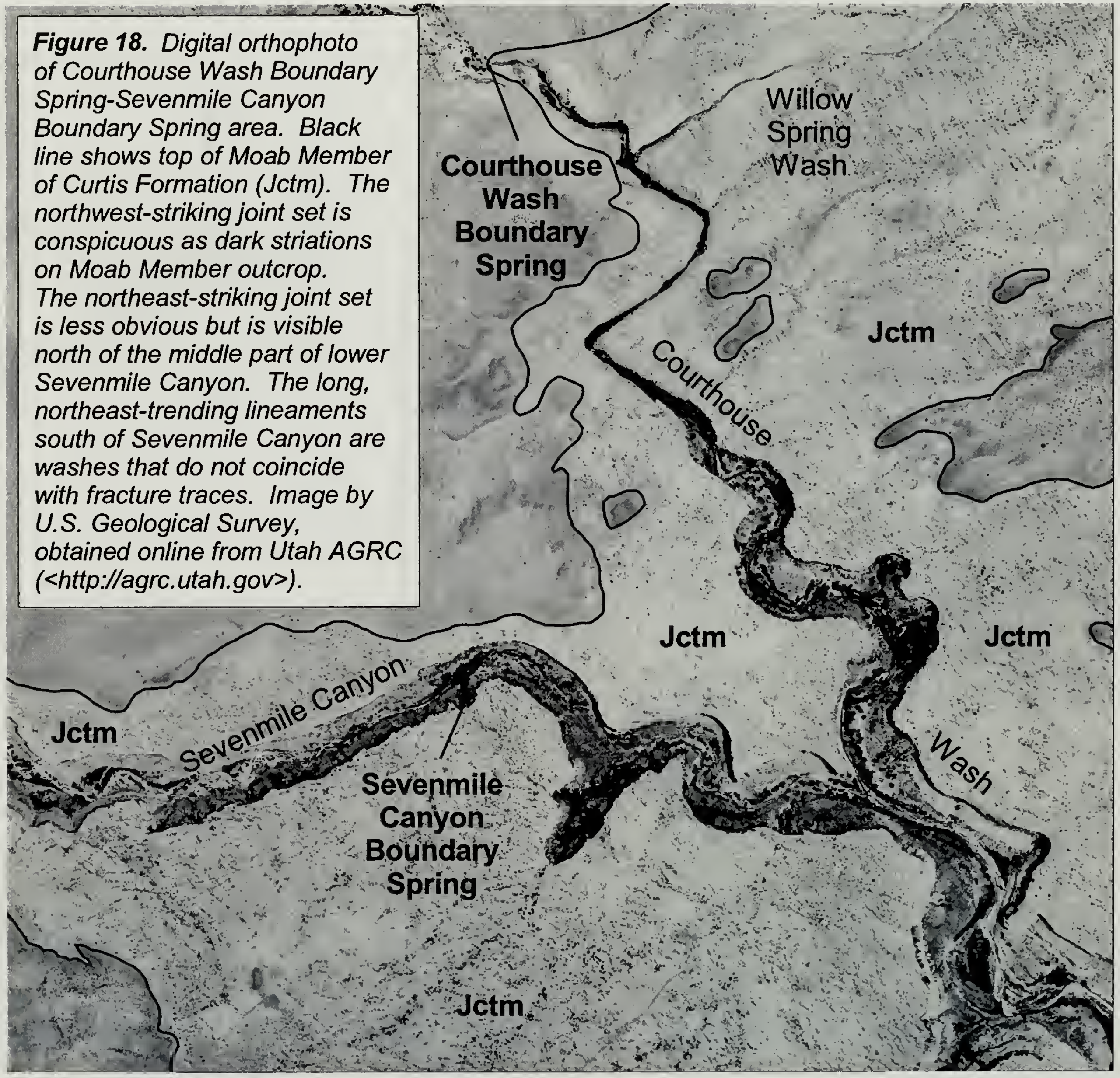
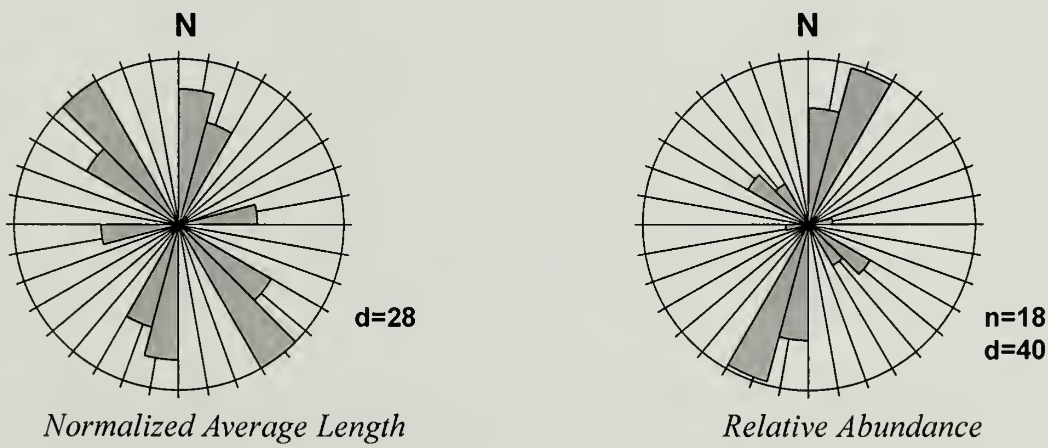



***Figure 18.*** *Digital orthophoto of Courthouse Wash Boundary Spring-Sevenmile Canyon Boundary Spring area. Black line shows top of Moab Member of Curtis Formation (Jctm). The northwest-striking joint set is conspicuous as dark striations on Moab Member outcrop. The northeast-striking joint set is less obvious but is visible north of the middle part of lower Sevenmile Canyon. The long, northeast-trending lineaments south of Sevenmile Canyon are washes that do not coincide with fracture traces. Image by U.S. Geological Survey, obtained online from Utah AGRC (<http://agrc.utah.gov>).*


*A. Site S1 near Courthouse Wash Boundary Spring.*




*B. Site S2 Cedar Point.*

***Figure 19.***

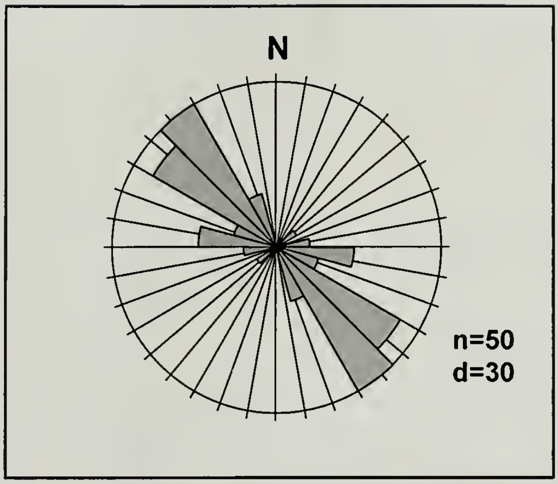
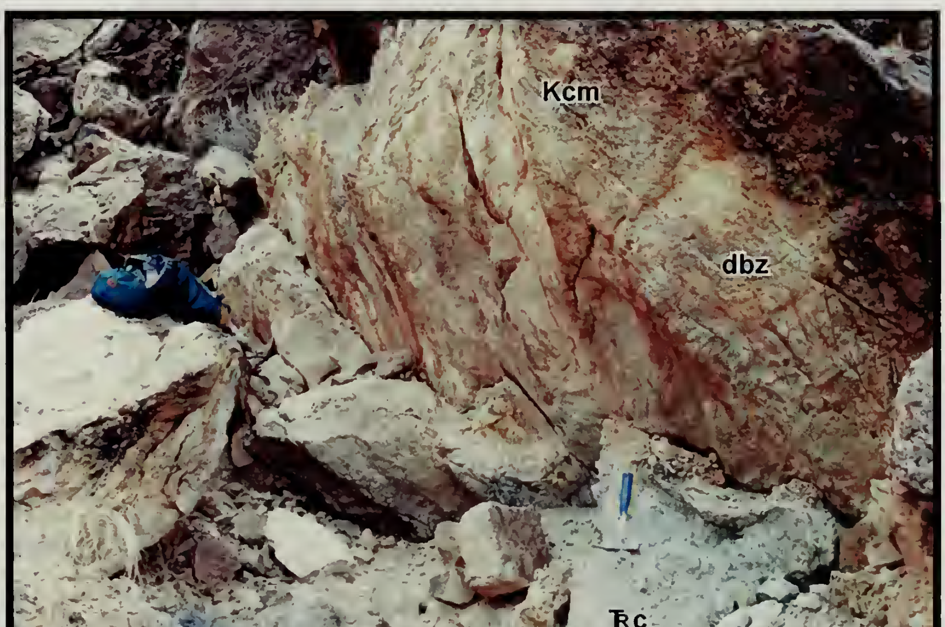



*Figure 20.*

21A



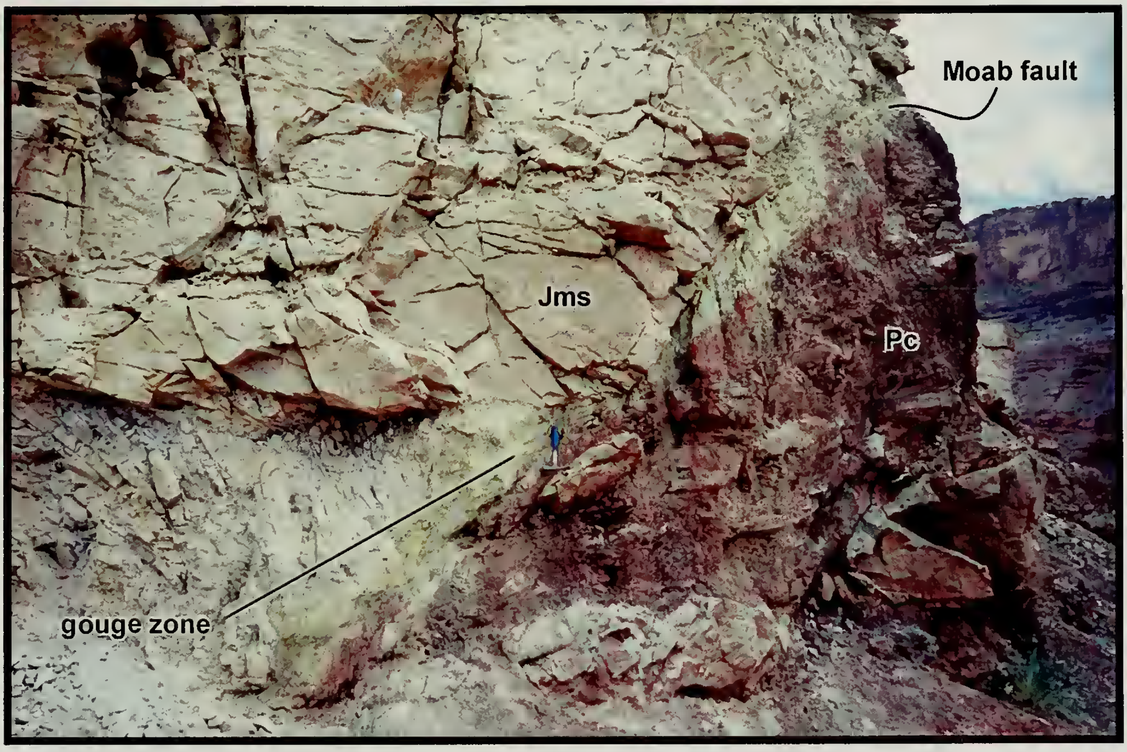
21B

*Figure 21.*


*21C*

*21D*

***Figure 21** (continued).*




*21E*

***Figure 21** (continued).*

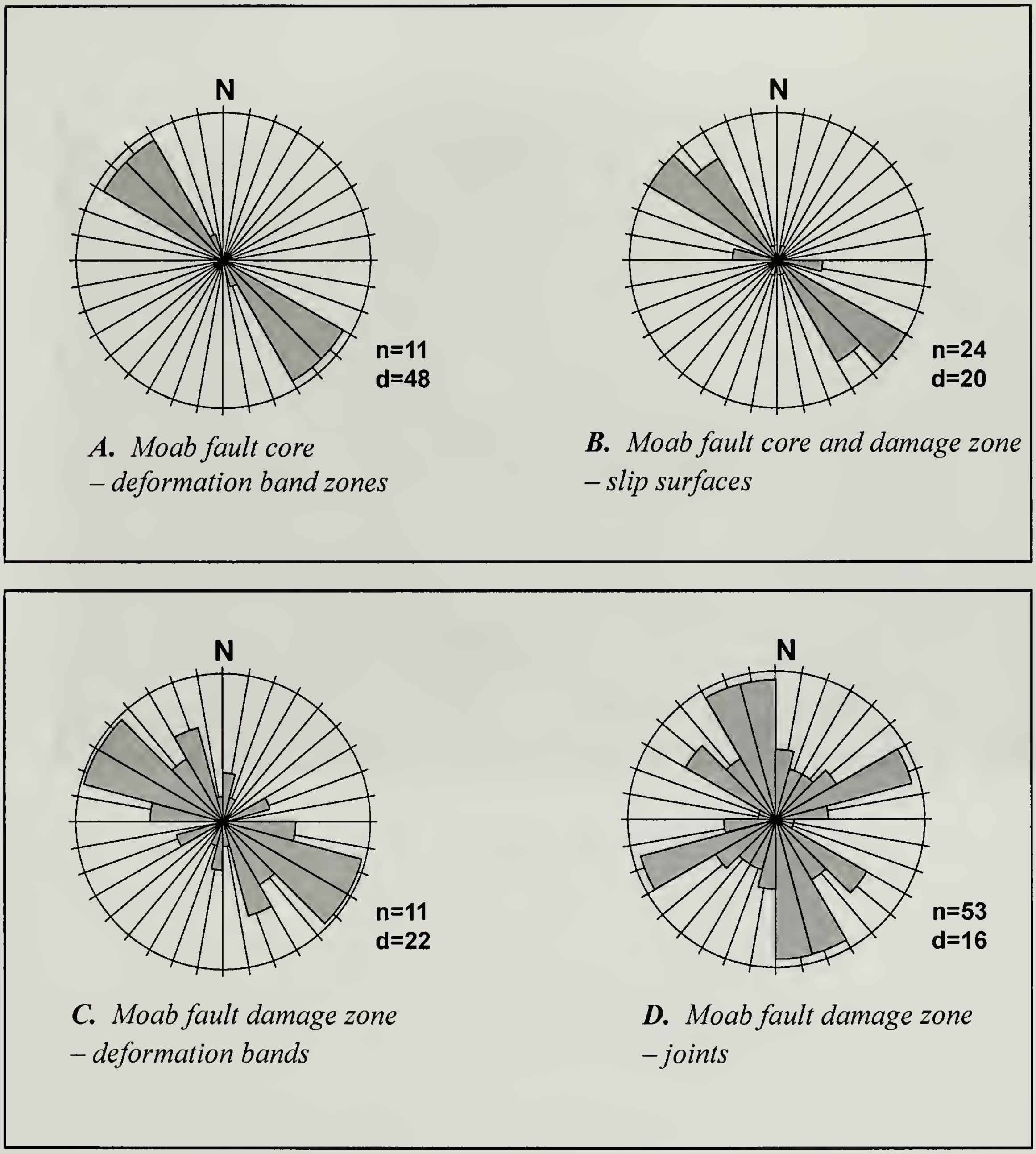

N
n=11
d=48
A. Moab fault core
– deformation band zones
N
n=24
d=20
B. Moab fault core and damage zone
– slip surfaces
N
n=11
d=22
C. Moab fault damage zone
– deformation bands
N
n=53
d=16
D. Moab fault damage zone
– joints

*Figure 22.*

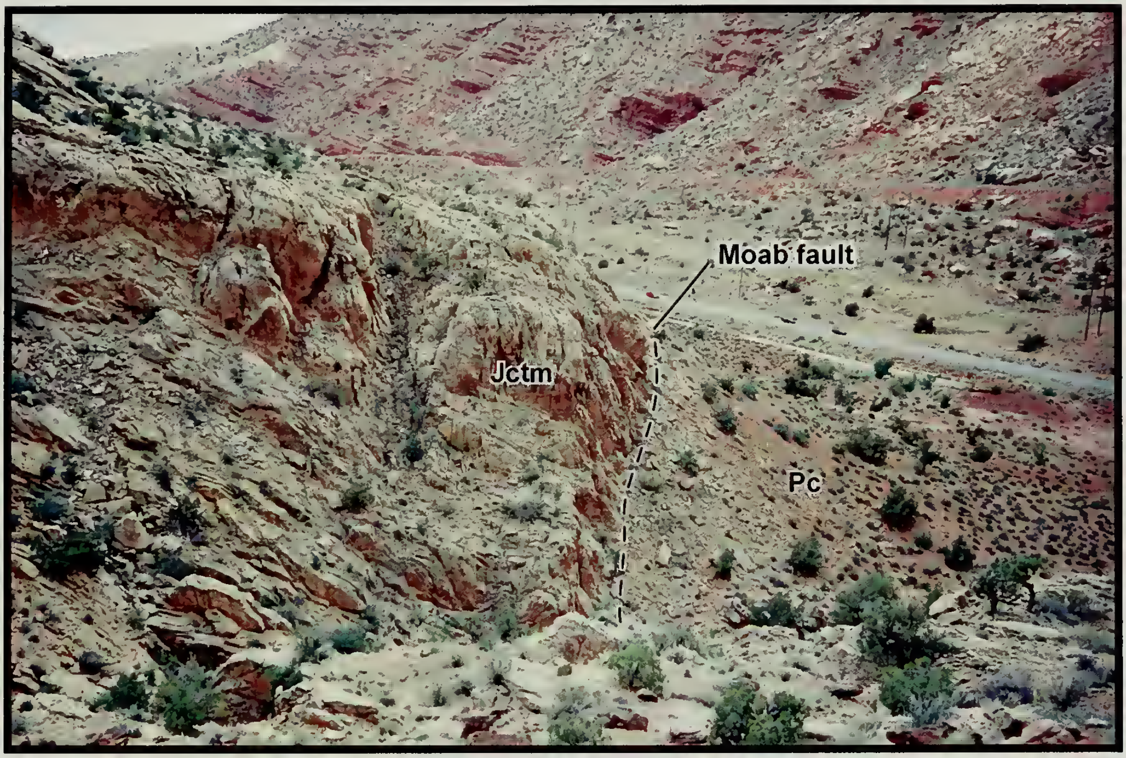



*Figure 23.*

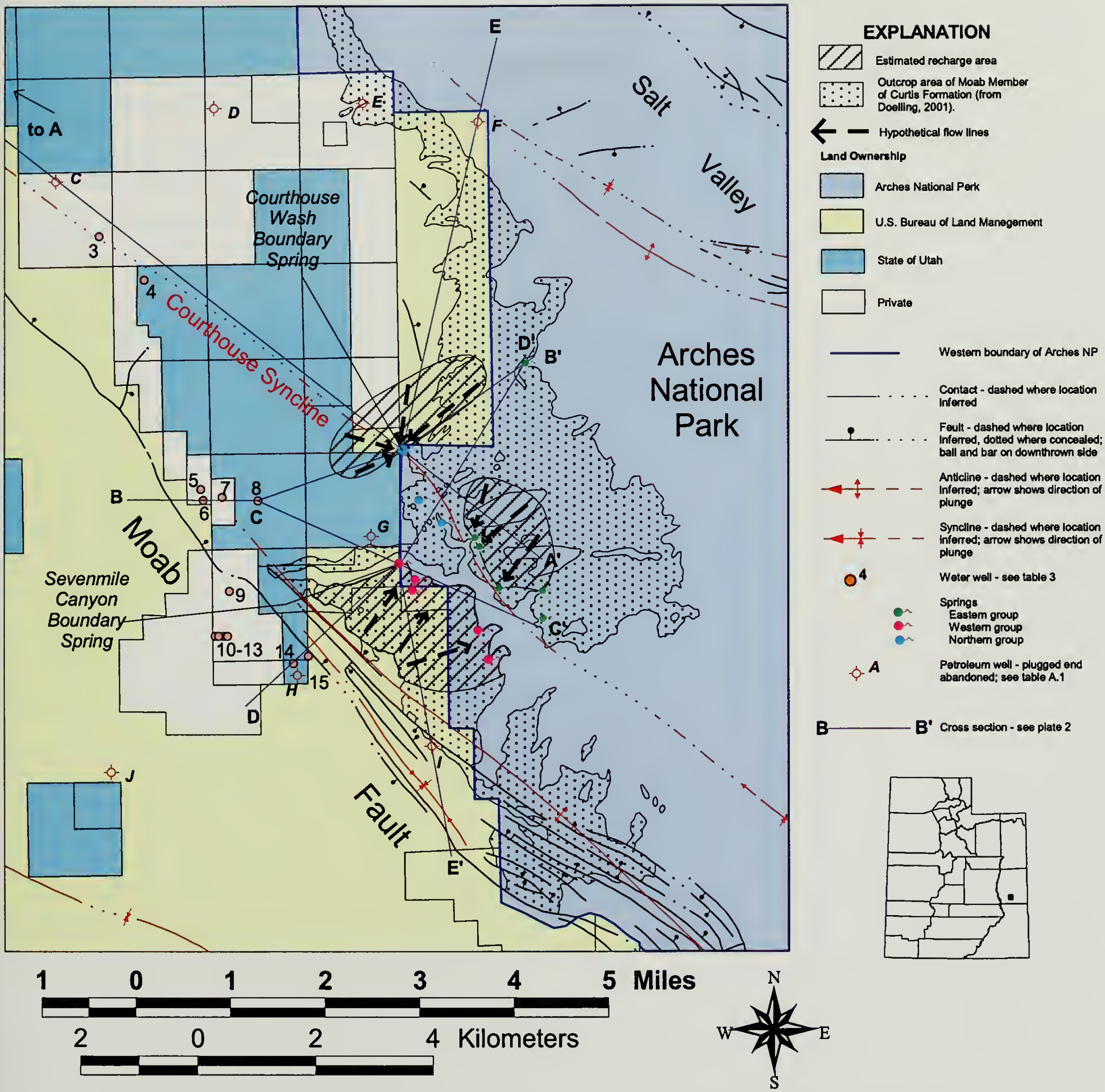



*Figure 24. Schematic representation of estimated recharge areas for the eastern and western spring groups and Courthouse Wash Boundary Spring.*

# APPENDIX

| Era | Period | | Epoch | Age | Age estimates in Ma[1] |
|---|---|---|---|---|---|
| Cenozoic | Quaternary | | Holocene | | 0.01 |
| | | | Pleistocene | | 1.6 |
| | Tertiary | Neogene | Pliocene | | 5.3 |
| | | | Miocene | | 23.7 |
| | | Paleogene | Oligocene | | 36.6 |
| | | | Eocene | | 57.8 |
| | | | Paleocene | | 66.4 |
| Mesozoic | Cretaceous | | Late | Maastrichtian | 74.5 (4) |
| | | | | Campanian | 84.0 (4.5) |
| | | | | Santonian | 87.5 (4.5) |
| | | | | Coniacian | 88.5 (2.5) |
| | | | | Turonian | 91.0 (2.5) |
| | | | | Cenomanian | 97.5 (2.5) |
| | | | Early | Aptian | 113 (4) |
| | | | | Albian | 119 (9) |
| | | | | Neocomian | 144 (5) |
| | Jurassic | | Late | | 163 (15) |
| | | | Middle | | 187 (34) |
| | | | Early | | 208 (18) |
| | Triassic | | Late | | 230 (22) |
| | | | Middle | | 240 (22) |
| | | | Early | | 245 (20) |

1. *Age estimates are from Palmer (1983), with uncertainties in parentheses, except where none are reported.*

| Era | Period | Epoch | Age | Age estimates in Ma[1] |
|---|---|---|---|---|
| | | | | 245 (20) |
| Paleozoic | Permian | Late | | 258 |
| | | Early | | 286 (12) |
| | Pennsylvanian | Late | | 296 (10) |
| | | Middle | | 315 (20) |
| | | Early | | 320 |
| | Mississippian | Late | | 352 (8) |
| | | Early | | 360 (10) |
| | Devonian | Late | | 374 (18) |
| | | Middle | | 387 (28) |
| | | Early | | 408 (12) |
| | Silurian | Late | | 421 (12) |
| | | Early | | 438 (12) |
| | Ordovician | Late | | 458 (16) |
| | | Middle | | 478 (16) |
| | | Early | | 505 (32) |
| | Cambrian | Late | | 523 (36) |
| | | Middle | | 540 (28) |
| | | Early | | 570 |
| Proterozoic | Late Proterozoic | | | 900 |
| | Middle Proterozoic | | | 1600 |
| | Early Proterozoic | | | 2500 |
| Archean | Late Archean | | | 3000 |
| | Middle Archean | | | 3400 |
| | Early Archean | | | 3800? |

***Figure A.1.*** *Geologic time scale, after Palmer (1983) and Hansen (1991).*

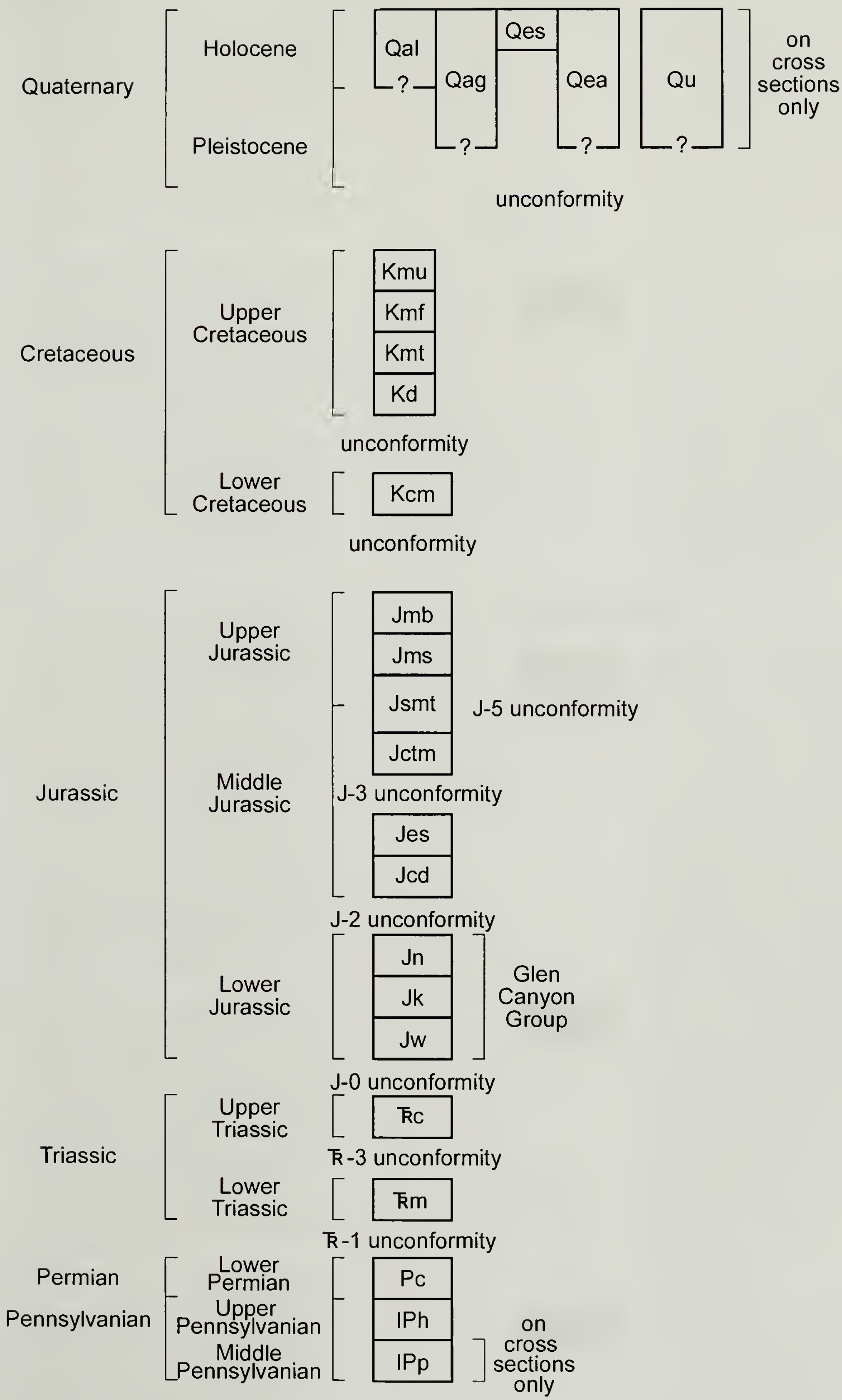



***Figure A.2.*** *Correlation of geologic units.*

# DESCRIPTION OF GEOLOGIC UNITS *from Doelling (2001)*

## Quaternary Deposits

**Qal** Stream alluvium -- Sand, silt, clay, granules, pebbles, and sparse cobbles adjacent to more active stream courses; unconsolidated, poorly to well-sorted channel-fill and low terrace deposits; thickness varies widely, but commonly less than 10 meters (33 ft) thick; Holocene to late Pleistocene.

**Qag** Alluvial gravel, undifferentiated -- Clast sizes vary from deposit to deposit; no particular geomorphic form or location; thickness commonly 5 meters (16 ft) or less.

**Qea** Mixed eolian and alluvial deposits -- Sand and silt of eolian origin interspersed with silt, sand, and gravel of fluvial origin; generally dominated by eolian deposits; commonly displays a well-developed caliche soil horizon at the top; thickness 10 meters (33 ft) or less; Holocene to middle Pleistocene.

**Qes, Qed** Eolian deposits -- Well-sorted sand and silt; deposited in sheets (Qes) and dunes (Qed); commonly fills hollows in sandstone outcrops or collects on the lee sides of cliffs and slopes; thickness 15 meters (50 ft) or less; mostly Holocene.

## Cretaceous Rocks

**Kmu, Kms** Upper shale (Blue Gate) member of Mancos Shale -- Mostly light- to dark-gray, marine, thinly laminated to thin-bedded, slope-forming shale, mudstone, and siltstone interbedded with subordinate yellow-brown to yellow-gray, mostly very fine- to fine-grained calcareous sandstone that crops out in several thin mappable (Kms) zones of subtle ledges and cliffs; the middle, more sandy part of the upper shale member that contains most of the ledges is the Prairie Canyon Member of Cole and others (1997); zone of thin-bedded, fine-grained sandstone at top; lower contact with Ferron Sandstone Member is gradational; about 1,020 meters (3,350 ft) thick; Campanian to Turonian.

**Kmf** Ferron Sandstone Member of Mancos Shale -- Brown-gray to yellow-gray, marine, fine-grained sandstone, sandy mudstone, and carbonaceous shale; fissile to thin bedded; generally forms two sandstone cuestas with a slope of dark-gray to black carbonaceous shale between them; locally fossiliferous; lower contact is a subtle scour surface locally overlain by lenticular lag deposits of pebbly, medium- to coarse-grained sandstone; 15 to 40 meters (50-130 ft) thick; Turonian.

**Kmt** Tununk Shale Member of Mancos Shale -- Light- to dark-gray, marine shale or mudstone; contains fine-grained sandy zones, especially near the top; slope forming; locally contains concretionary Coon Springs Bed in the upper third of the unit; lower contact with Dakota is abrupt but conformable. The lower contact is an unconformity where the Dakota is missing (Western exposures) and marked by change from green (Cedar City Fm.) to gray shale; 45 to 120 meters (145-390 ft) thick, generally thicker to west; Turonian to Cenomanian.

**Kd** Dakota Sandstone -- Yellow-gray to brown sandstone, conglomeratic sandstone, and conglomerate interbedded with gray mudstone, carbonaceous shale, coal, and claystone; commonly forms cliffs and ledges; commonly divisible in the east part of the quadrangle into upper and lower cliff-forming sandstone and conglomerate and a middle, slope-forming mudstone unit; scoured into the Cedar Mountain or Burro Canyon Formations; 0 to 37 meters (0-120 ft) thick, discontinuous in west part of quadrangle, thickens eastward; Cenomanian.

**Kcm** Cedar Mountain Formation -- Drab olive-green to variegated mudstone and brown to gray sandstone, gritstone, conglomerate, and limestone; mudstone is slope forming, other rock types form ledges; locally contains petrified wood; lower contact (unconformity) is placed at base of a prominent sandstone or conglomerate ledge or cliff above the brighter variegated mudstone of the Brushy Basin Member of the Morrison Formation; correlative with the Burro Canyon Formation; 12 to 76 meters (40-250 ft) thick, thins irregularly eastward; Albian.

## Jurassic Rocks

**Jmb** Brushy Basin Member of Morrison Formation -- Variegated (purple, green, white, orange) mudstone interbedded with gray, white, or brown conglomeratic sandstone, conglomerate, nodular limestone, and gritstone; slope forming with subtle ledges; purple and lavender hues dominate in most areas, but bright green dominates in Cache Valley and in the southern part of the Salt Valley anticline; layers of bentonitic claystone are common, outcrops are generally prone to slumping; lower contact placed at the base of the mudstone sequence or at the base of the lowest conglomerate ledge; 90 to 135 meters (295-450 ft) thick; Upper Jurassic.

**Jms** Salt Wash Member of Morrison Formation -- Light-yellow-gray sandstone interbedded with red and gray mudstone and siltstone; sandstone is fine to coarse grained, cross-bedded, and forms medium to thick lenses; mudstone and siltstone form slopes or recesses between sandstone ledges; lower contact at base of first thick sandstone bed above the red or lavender siltstone of the Tidwell Member of the Morrison Formation; locally intertongues with Tidwell siltstones; 40 to 90 meters (130-300 ft) thick; Upper Jurassic.

**Jsmt** Tidwell Member of Morrison Formation and Summerville Formation, undivided -- Divisible in field, but too thin to map separately at the 1:100,000 scale. Tidwell Member (Jmt) consists of calcareous, thin-bedded lavender, maroon, and light-gray siltstone, light-gray, thin- to thick-bedded, very fine-grained sandstone, and gray thin-bedded or nodular limestone; all slope forming; limestone locally contains large white chert concretions; west of 110° W., locally intertongues with thick white

## Jurassic Rocks *(continued)*

gypsum bodies; 6 to 20 meters (20-65 ft) thick. Summerville unconformably (J-5 unconformity) overlain by Tidwell Member. In areas where combined with the Tidwell, the Summerville is gray, tan, brown, and red, mostly fine-grained, thin-bedded sandstone and siltstone that forms a steep slope and becomes ledgy near the top; 2-21 meters (6-69 ft) thick. Upper and Middle Jurassic.

Jctm

Moab Member of Curtis Formation (member of Entrada Sandstone on previous maps) -- Light-yellow-gray, fine- to medium-grained, cross-bedded, massive, and cliff-forming sandstone; forms a tongue between the Summerville and Entrada Formations and pinches out in the western part of the quadrangle; rests directly on the Slick Rock Member in the east; the lower contact with the Slick Rock Member of the Entrada Sandstone is placed at the base of a prominent parting or a subtle line, probably the J-3 unconformity of Pipiringos and O'Sullivan (1978), which has considerable relief in the Dewey area; 0 to 42 meters (0-138 ft) thick (including the main Curtis where both are present); Middle Jurassic.

Jes

Slick Rock Member of Entrada Sandstone -- Mostly orange-red or banded orange-red and white sandstone; generally fine grained, eolian cross-bedded; massive with local discontinuous partings; resistant and smooth weathering, but not as resistant as the Moab Member of the Entrada Sandstone; locally pocked with abundant small spherical holes (with diameters up to 10 centimeters) in outcrop; the lower contact is commonly crenulated or contorted above the darker red-brown sandstone of the Dewey Bridge Member of the Carmel Formation; 43 to 152 meters (140-500 ft) thick, thinning eastward; Middle Jurassic.

Jcd

Dewey Bridge Member of Carmel Formation (member of Entrada Sandstone on previous maps) -- Upper half is dark-red, muddy, earthy, fine-grained sandstone; lower half is interbedded dark-red, red-brown, light-brown, and yellow-gray, fine- to medium-grained sandstone; upper half commonly has contorted, nodular, or indistinct bedding and locally contains white beds; upper half forms slopes or recesses between the overlying Slick Rock Member of the Entrada Sandstone and the lower half; lower half is more resistant, is commonly calcareous and cherty, and forms scabs on the underlying Navajo Sandstone; yellow-gray beds in the lower half resemble the underlying Navajo Sandstone, but are flat bedded; lower half is locally missing, especially in the east; lower contact is the J-2 unconformity of Pipiringos and O'Sullivan (1978); 8 to 72 meters (25-235 ft) thick, generally thinning eastward; Middle Jurassic.

Jn Jnl

Navajo Sandstone -- Mostly light-hued, fine- to medium-grained, eolian cross-bedded, massive sandstone; lower third commonly weathers to a cliff, the remainder into domes and rounded knolls; locally contains thin, hard, gray limestone beds (Jnl); lower contact placed at the top of a thick, white to pink sandstone in the Kayenta Formation; 0 to 225 meters (0-740 ft) thick, pinches out to the northeast over the Uncompahgre uplift; Lower Jurassic.

Jk

Kayenta Formation -- Red-brown, lavender-gray, fine- to coarse-grained, medium- to thick-bedded sandstone; contains local white and dark-brown beds, intraformational conglomerate, and limestone; forms thick ledges; generally contains abundant red slope-forming siltstone in upper third; lower contact is a scoured surface in the massive orange-brown Wingate Sandstone; 30 to 90 meters (100-300 ft) thick; Lower Jurassic.

Jw

Wingate Sandstone -- Orange-brown, dark-brown-weathering, fine-grained, massive sandstone; forms vertical cliff along canyon walls, commonly stained with desert varnish; abrupt contact with underlying Chinle Formation placed at base of massive, cliff-forming sandstone or on top of thick, orange-brown, flat-bedded sandstone (J-0 unconformity) below which typical Chinle slope-forming siltstones and sandstones are found; 75 to 137 meters (250-450 ft) thick; Lower Jurassic.

## Triassic Rocks

₮c

Chinle Formation -- Red-brown sandstone, siltstone, conglomeratic sandstone, and mudstone; forms steep slope with Moenkopi Formation below; has basal member of quartzose gritstone or sandstone and mottled siltstone and sandstone beneath an unconformity; contains multiple intraformational unconformities adjacent to salt diapirs; lower contact is the ₮-3 unconformity of Pipiringos and O'Sullivan (1978), which is slightly angular; 0 to 275 meters (0-900 ft) or more thick, greatest thickness in rim synclines adjacent to salt-cored anticlines and locally missing on anticlines; only 12 to 30 meters (40-100 ft) cover Precambrian rocks on the Uncompahgre uplift to the northeast; Upper Triassic.

₮m

Moenkopi Formation -- Red-orange, chocolate-brown, and medium-brown sandstone, silty sandstone, and minor siltstone and conglomerate; generally divisible into two to four members, but are undivided on the map; lower contact is the ₮-1 unconformity of Pipiringos and O'Sullivan (1978), which is slightly angular and is found at the top of the more red-brown sandstone of the underlying Cutler Formation; total thickness is 0 to 400 meters (0-1,300 ft) or more, thinning regionally eastward and may be missing on the Uncompahgre uplift in the northeast and very thick in rim synclines adjacent to salt-cored anticlines; Middle (?) to Lower Triassic.

## Permian Rocks

Pc

Cutler Formation -- Interbedded red-brown subarkosic, arkosic, and micaceous sandstone and lavender-brown conglomerate; sandstone is fine to coarse grained and gritty in eastern exposures; low- to high-angle cross-beds, thin bedded to massive, and forms smooth and rounded ledges; conglomerate is mostly pebbles to 13-centimeter (5-inch) cobbles, but cobbles exceeding 30 centimeters (1 ft) or more in diameter are common in the eastern part of the quadrangle; mostly quartzite, granite, felsite, gneiss, and schist clasts; matrix is poorly sorted, fine- to coarse-grained sandstone, with grains of quartz, lithic fragments, mica, feldspar, and unidentified black minerals; laminated to indistinct bedding; weathers to smooth irregular slopes or gentle ledges; lower contact is placed above a gray limestone ledge that contains Late Pennsylvanian (Virgilian) fusulinids; 0 to 2,450 meters (0-8,000 ft) thick; missing over some salt-cored anticlines, thickest at the west edge of the Uncompahgre uplift; as much as 1,000 meters (3,300 ft) exposed; 75 meters (245 ft) of gray-white, cross-bedded quartzose sandstone at the top of the Cutler Formation in the north part of the southwest flank of Castle Valley may be an outcrop of White Rim Sandstone; Lower Permian.

## Pennsylvanian Rocks

IPh

Honaker Trail Formation -- Interbedded sandstone, siltstone, limestone, and subarkosic sandstone; limestone is commonly fossiliferous; the lower contact is not exposed, but the unit is juxtaposed against Paradox Formation caprock on the southwest flank of the Onion Creek salt-cored anticline; 0 to 1,525 meters (0-5,000 ft) or more thick, thickening eastward to the west edge of the Uncompahgre uplift, missing on the Uncompahgre uplift and over some salt-cored anticlines; maximum surface thickness is less than 300 meters (985 ft); Upper Pennsylvanian (Virgilian-Missourian).

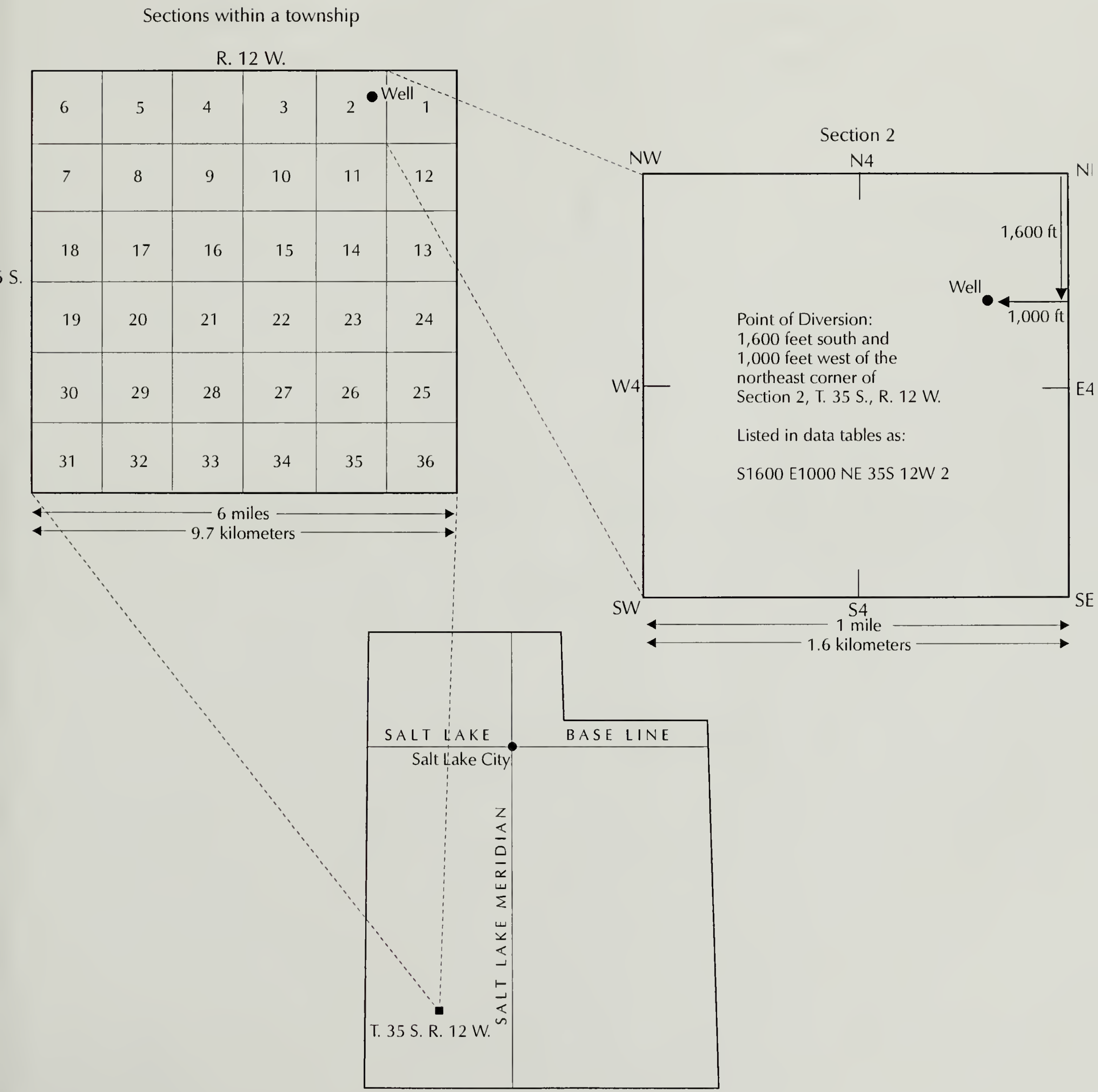



***Figure A.3.*** *Numbering system for wells in Utah - Point of Diversion convention.*

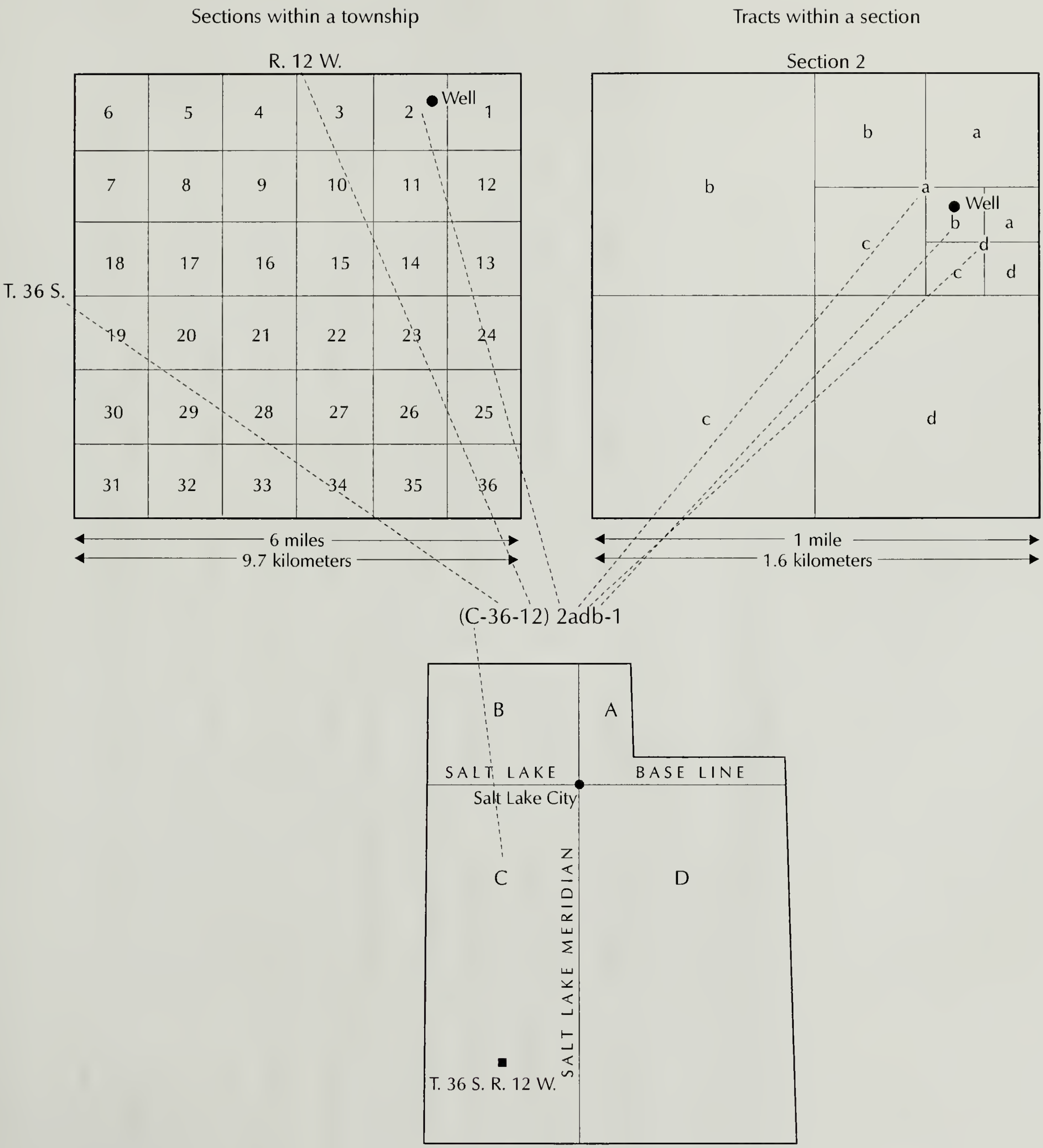



*Figure A.4. Numbering system for wells in Utah - U.S. Geological Survey convention.*

*Table A.1*. *Records of oil-test wells in study area*[1].

| ID[2] | Operator | Well Name | API Number | Township | Range | Section | Spot[3] | Elevation | Total Depth | Log[4] |
|---|---|---|---|---|---|---|---|---|---|---|
| A | EQUITY OIL COMPANY | 1 STATE | 4301910361 | 23 S | 19 E | 36 | 1650 FSL 330 FEL | 4585 | 6769 | Kd 320; Jms 862; Js 959; Jctm 1605; Jcd 1726; Jn 2172; Jk 2544; Jw 2708; TRc 3070; TRm 3780 |
| B | SHELL OIL COMPANY | 1 LEGGETT | 4301911035 | 24 S | 20 E | 12 | 1715 FNL 1673 FEL | 4636 | 5600 | Jn 90; Jk 536; Jw 593; TRc 940; TRm 1398; Pc 1575; IPh 3097; IPp 4426 |
| C | GREAT LAKES CARBON CORP | 1 STATE | 4301911472 | 25 S | 20 E | 2 | 300 FSL 660 FEL | 4598 | 3665 | Jctm 754; Jn 1307; Jk 2237; Jw 2335; TRc 2618; TRm 3544; Pc 4465; IPh 6708; IPp 8678 |
| D | UNION OIL CO OF CALIFORNIA | 1 STATE | 4301930032 | 24 S | 20 E | 36 | 575 FSL 1836 FEL | 4434 | 7534 | Jn 1720; TRc 2545; TRm 3395; Pc 5478; IPh 9170 |
| E | GENERAL CRUDE OIL CO | 1 BIG ROCK-BARTLETT | 4301930050 | 25 S | 19 E | 26 | 820 FNL 615 FEL | 5436 | 8875 | Jctm 150; Jn 680; Jk 1180; Jw 1410; TRc 1810; TRm 2535; Pc 5115 |
| F | FERGUSON & BOSWORTH | 1 CULLEN-HS PET-GOVT | 4301930122 | 24 S | 21 E | 7 | 660 FNL 660 FEL | 4845 | 4964 | Jk 885; Jw 1173; TRc 1570; TRm 2380; Pc 4809 |
| G | MOUNTAIN FUEL SUPPLY CO | 2 KLONDIKE UNIT | 4301930272 | 24 S | 19 E | 22 | 1860 FSL 793 FEL | 4765 | 7830 | Jctm 46; Jcd 520; Jn 680; Jk 1570; Jw 2004; TRc 2254; TRm 2929; Pc 3228; IPh 5444 |
| H | ARI-MEX OIL & EXPLOR INC | 1-7 SKIP-FEDERAL | 4301930418 | 25 S | 21 E | 7 | 1742 FSL 1557 FWL | 4738 | 2300 | IPp 2900 |
| I | TIGER OIL CO | 12-11 STATE | 4301930455 | 24 S | 20 E | 11 | 1980 FNL 660 FWL | 4927 | 12357 | Jctm 300; Jcd 400; Jn 560; Jk 1580; Jw 1680; TRc 2010; TRm 2170 |
| J | CHANDLER & ASSOC. INC. | 16-9 MOAB-FEDERAL | 4301930910 | 25 S | 20 E | 9 | 388 FSL 547 FEL | 4996 | 9968 | IPp 4496 |
| K | LADD PETROLEUM CO. | 1 SALT VALLEY | 4301931112 | 24 S | 20 E | 16 | 500 FNL 2130 FWL | 4456 | 11330 | TRc 468; TRm 837; Pc 1375; IPh 2861; IPp 4406 |

**Notes**
1. Data from Utah Division of Oil, Gas and Mining records.
2. Corresponds to letters on figures 3 and 6 and plates 1A and 1B.
3. Distances in feet from north (FNL), south (FSL), east (FEL), and west (FWL) section boundaries.
4. Values are depth to top of formation in feet below reference elevation. Unit abbreviations are map symbols shown on figures 3 and 6 and plates 1a and 1b.